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AN EMPIRICAL STUDY OF THE IMPACT OF A PRODUCTION RATE CHANGE ON THE DIRECT LABOR REQUIREMENTS FOR AN AIRFRAME MANUFACTURING PROGRAM

LSSR 23-77B

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This study examined the impact on direct labor requirements resulting from externally caused production rate changes in the T-38/F-5 airframe production program. The basis for the study was the research conducted at the University of Oregon by Lieutenant Colonel Larry L. Smith in 1975-76. He used a modification to the standard learning curve model and devised a procedure to determine the forecasting ability of the model using data from the F-4, F-102, and KC-135 programs. Smith found that production rate, as expressed in his modified model, showed a significant inverse relationship to direct labor requirements. Additionally, his model provided substantially improved labor requirement forecasts as compared to corresponding forecasts provided by the standard learning curve model. In this study, which replicated Smith's research using T-38/F-5 data, Smith's findings and conclusions were validated. Based on the consistency of findings, Smith's model is recommended for use in forecasting direct labor requirements in an active airframe production program.

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AN EMPIRICAL STUDY OF THE IMPACT OF A PRODUCTION RATE CHANGE ON THE DIRECT LABOR REQUIREMENTS FOR AN AIRFRAME MANUFACTURING PROGRAM

A Thesis

Presented to the Faculty of the School of Systems and Logistics

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In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Facilities Management

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Chapter 1

INTRODUCTION AND OVERVIEW

The history of cost overruns in the acquisition of complex weapon systems indicates a significant cost estimating problem within the Department of Defense (DoD). This problem is manifested in several ways, two of which are most discouraging. First, production deceleration or possibly termination is necessary if additional funds cannot be budgeted. A second, and possibly worse manifestation is the loss of public trust and support for the DoD when overruns are perceived to be the result of wasteful mismanagement. Given that DoD budget cutting is a current political theme, the DoD can ill-afford any avoidable adverse publicity. In this context, the need for more accurate cost estimating techniques is quite clear.

The Complexity of Accurate Cost Estimation

Since cost estimation relies on forecasting future events and trends, the entire process is plagued with uncertainty. A common practice is to identify historical trends and project them into the future.

This practice is reliable when future trends are consistent with those in the past. However, since the future is filled with unpredicted events and complications, projection of past trends into the future often produces unreliable estimates.

In aircraft production many complexities arise during the life of the production program. For instance, it is sometimes necessary to alter the programmed rate of production. An excerpt from a recent RAND report pinpoints this problem:

> The prime requirement for efficient production--a stable, fairly long production run--is usually lacking in the airframe industry. Plans are made to produce at one rate, and then because of design problems, cost growth, funding problems, modifications, etc., the rate is changed. Decisions on rate of output are based on military, financial, and political considerations, not efficiency of production [7:8].

Limiting the Problem

During initial contract negotiations for an aircraft production program, a tentative monthly delivery schedule is developed for the life of the program. However, formal contractual agreements between the DoD and the contractor are usually limited to the first year's delivery requirements. Delivery rates for subsequent years are to a large extent determined by the amount

of program funds appropriated from year to year by the Congress (11:2). Specifically, the funds appropriated may be more or less than the amount needed to maintain the delivery schedule which was negotiated at the outset of the program. One result of such budget changes is acceleration or deceleration of the delivery schedule for the subsequent year. Since the contractor has estimated his production resource requirements on the tentative production schedule, changes in that schedule will require him to evaluate the new requirements and their associated costs. The DoD must similarly reevaluate its cost estimates as a basis for negotiating contract revisions.

One estimate requiring revision involves the direct labor requirement costs associated with fabricating and assembling each airframe[1] under the revised delivery schedule. The traditional approach to estimating these labor requirements involves the use of "learning curve" theory.

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[1]The airframe can be viewed as an accounting entity that encompasses the manufacturer's production responsibility. For example, airframe costs would not include the direct labor hours required to produce engines and avionics but would include the hours required to install those components. In contrast, aircraft costs would include all the costs associated with producing the aircraft [11:3].

The theory of the learning curve in a popular form states that "as the total quantity of units produced doubles, the cost per unit declines by some constant percentage [1:1]." When this theory is applied to direct labor requirements, the term "cost" in the above definition is commonly replaced with "direct labor man-hours per pound of airframe."[2] For simplicity, this lengthy phrase will often be shortened to "labor hours" or "direct labor hours" in future references.

Although this traditional learning curve theory is still widely used, it does not systematically consider the impact of anticipated production rate changes resulting from delivery schedule revisions. In other words, the impact of the acceleration or deceleration of learning opportunities that an explicit production rate change would cause is not incorporated in the traditional theory. Concern over this apparent discrepancy has resulted in numerous approaches to incorporate a production rate factor in labor hour estimation formulas.

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[2] Using this expression as a proxy for "cost" divorces the complicating effects of fluctuating wage rates from the estimation process. After labor hour requirements have been estimated, the expected hourly wage rates can then be used to estimate the actual dollar costs (3:5).

Most of these approaches are modifications to the traditional learning curve theory, but none have received general acceptance. One reason that none have been widely accepted is probably because of divergent research results obtained using the various approaches (11:15). However, of particular interest are the research efforts from 1969 to 1976 by Gordon J. Johnson (6), Joseph A. Orsini (10), Joseph W. Noah (8), and Larry L. Smith (11) which yielded compatible results.

Although each of these individuals concluded from their research that direct labor requirements were significantly affected by production rate changes, Smith's approach and findings are the most promising for extended research. The basis for this assertion is that Smith's approach was validated by analysis of historical production data from the F-4, F-102, and KC-135 programs, and as he suggested, "an obvious extension of this research effort is to duplicate the procedure on additional programs [11:146]."

The Research Problem Statement

Replication of Smith's labor hour estimation approach, using historical data from different production programs, is needed to further validate his approach.

Research Objectives

The prime objective is to identify the impact on direct labor requirements resulting from externally caused production rate changes in an ongoing production program. If this primary objective is accomplished, a second objective of further validating Smith's approach will be concurrently achieved.

Summary

With the problem narrowed, and objectives outlined, the next chapter is devoted to a review of past research approaches and findings. Chapter 3 discusses the research hypotheses and the methodology for testing these hypotheses. Chapter 4 discusses the T-38/F-5 data and presents the results of analysis and hypothesis testing. Chapter 5 summarizes this research effort with a discussion of interpretations and conclusions.

Chapter 2

A HISTORY OF LABOR REQUIREMENT ESTIMATING TECHNIQUES

This chapter traces the history and development of traditional learning curve cost estimating techniques as well as the development of four modifications to the standard technique. The major emphasis is placed on the research efforts of Johnson, Orsini, Noah, and Smith since their findings are compatible, and as such form the basic justification for this research. Smith's research is given particular emphasis, since his method will be replicated.

Standard Learning Curve Cost Model

Mathematical modeling of the learning curve theory is generally credited to T. P. Wright who published his work in 1936. Harold Asher reports that Wright's model was $\bar{Y} = AX^B$, where:

$\bar{Y}$ represents the cumulative average direct man-hours,

X represents the cumulative number of airframes produced,

A represents the direct man-hour cost of the first airframe, and

B is a negative exponent whose value reflects the slope[1] of the learning curve for a particular production program (1:16-17).

Asher further reports that following World War II, J. R. Crawford conducted studies of 200 jobs in the airframe manufacturing process. Crawford concluded from these studies that direct labor hours should be represented by $Y = AX^B$ where:

Y represents the direct man-hours for the Xth <u>unit</u> (as opposed to the cumulative average), and

A, X, and B have the same meaning as defined previously (1:21-24).

This second formulation is appropriately called the unit learning curve model, and will be referred to as the standard model for the remainder of this paper.

<u>Reason for Continued Use</u>

Although the standard model is non-linear in its normal form, it can be linearized through a logarithmic (log) transformation[2] where $\text{Log } Y = \text{Log } A + B \text{ Log } X$.

---

[1]The slope of the curve is described in terms of the percentage decrease in labor hours for each doubling of output. For example, if the labor required to produce the 100th unit is 80 percent of the labor required for the 50th unit, the slope of the curve is 80 percent. For each slope, the value of B is fixed (1:17).

[2]Any logarithm "base" can be used for the transformation.

This transformation is easily made by plotting untransformed curve points on "log-log" graph paper. For perfect model data, the curve would be transformed to a straight line. This facilitates visualization of relationships within the model, and permits rather simple mathematical computation and manipulation (5:1-5). These appealing characteristics have no doubt contributed to the model's widespread acceptance and continued use.

Standard Model Limitation

Although the standard model is still widely used, it does not systematically consider the impact on direct labor hours resulting from externally caused changes in production rate. Concern over this discrepancy has several intuitive justifications as follows: (1) Workers would seemingly be motivated to work faster if they sense management pressure to increase production rate. The reverse result also seems logical if a production slowdown is mandated; (2) Task specialization seems more likely as production rate increases and additional workers are hired. The reverse effect would be anticipated if production rate decreases; (3) Machine set-up times and tooling costs can be distributed over a greater number of airframes if production rate is high (1:87).

Recognition of these justifications for considering the impact of production rate is the DoD requirement for military weapon system development programs to tie production costs to a specific production rate as early as the conceptual phase of the program. Furthermore, the military service must consider the effect of production rate throughout the various phases of the acquisition process (7:1).

Development of Three-Dimensional (3-D) Cost Models

The 3-D cost models of importance to this research are those which modify the standard model by including a second independent variable to systematically account for production rate changes. In this context, the cost models and findings of Johnson, Orsini, Noah, and Smith are presented.

Gordon J. Johnson. Johnson used the following additive form model to predict labor requirements for rocket motors; $Y = A + BX_1 + CX_2^Z$, where:

Y represents the direct labor hours per month,

X_1 represents the production rate in equivalent units per month,

X_2 represents the cumulative units produced as of the end of each month, and

A, B, and C are coefficients determined by regression, and Z is assigned different values until an optimum regression coefficient of determination (R^2) is achieved (6:34-38).

Johnson reported that a logical physical interpretation of the regression coefficients was not made. The Z value was expected to approximate the negative slope exponent for the standard learning curve; however, the Z value

> . . . obtained in the proposed model suggests a slope of the order of 20%. This is substantially different from the usual improvement (learning curve) slopes of about 80% [6:37].

Johnson attributed this unexpected value of Z to the interaction of the other variables in his model which are not found in the standard model (6:38).

The results from regressing his model against the four rocket motor data sets are summarized in Table 1. Johnson reported that an inadequate labor accounting system, used by the manufacturer to generate data set three, was the probable reason for the low (.308) R^2 value. By discounting the results from data set three, Johnson concluded that production rate is a significant determinant of direct labor requirements (6:39).

Joseph A. Orsini. Orsini's initial objective was to determine the applicability of Johnson's model for airframe production by testing it against C-141 production data. The procedure employed was to regress Johnson's

Table 1

Summary of Johnson's Regression Analysis

Regression Variables	Coefficients of Determination (R^2)[a] Data Set 1	2	3	4
Labor hours vs Cumulative units	.753	.395	.00678	.763
Labor hours vs [Cumulative units & Production Rate]	.932	.808	.308	.927

[a]R^2 is a statistical value, ranging from 0 to 1, that reflects the efficiency of a regression model.

Source: (6:34).

model in its 3-D form and compare results with those obtained using a two-dimensional (2-D) form of the model with the production rate variable omitted (10:54-77).

To provide a second comparison point, Orsini then converted Johnson's model from the additive form to a multiplicative form. The resulting model was

$Y = e^{B_0} X_1^{B_1} X_2^{B_2}$ where:

Y represents the direct labor hours per quarter,

X_1 represents the number of units produced per quarter,

X_2 represents the cumulative units produced as of the end of each quarter,

B_0, B_1, and B_2 are regression coefficients, and e is the base of the natural logarithm system (10:66).

To facilitate regression, this model was transformed to a linear form by taking the natural logarithm of all terms where $\ln Y = B_0 + B_1 \ln X_1 + B_2 \ln X_2$. The results of regressing this model, and the two forms of Johnson's model, are summarized in Table 2.

The reason for the differing values of Z presented in Table 2 is that Orsini was concerned with the procedure of estimating the Z value and then treating it as a constant during regression. By regressing the standard model against the C-141 data, he determined that

Table 2

Summary of Orsini's Regression Analysis

Model	Value of Z[a]	Coefficient of Determination (R^2)	Coefficient of Partial Determination	
$Y = B_0 + B_1X_1 + B_2X_2^Z$	-.3219	.910	X_1: .705	X_2: .417
$Y = B_0 + B_2X_2^Z$	-.3219	.695	X_2: .695	
$Y = B_0 + B_1X_1 + B_2X_2^Z$	-.4529	.907	X_1: .769	X_2: .402
$Y = B_0 + B_2X_2^Z$	-.4529	.600	X_2: .600	
$Y = B_0 + B_1X_1 + B_2X_2^Z$	-1.3219	.882	X_1: .842	X_2: .237
$Y = B_0 + B_2X_2^Z$	-1.3219	.253	X_2: .253	
$Y = e^{B_0}X_1^{B_1}X_2^{B_2}$	--	.955	X_1: .613	X_2: .245
$Y = e^{B_0}X_2^{B_2}$	--	.883	X_2: .883	

[a]The three Z values and the slopes they represent are: -.3219 for 80 percent slope, -.4529 for 73 percent slope, and -1.3219 for 40 percent slope (10:71).

Source: (10:68-69).

the actual learning curve slope was 73 percent. Since R^2 was higher for the arbitrarily chosen 80 percent slope Z value (-.3219) than it was for the actual 73 percent slope Z value (-.4529), he questioned the worth of including Z in the model (10:71).

Orsini drew two conclusions from the results listed in Table 2. First, the production rate variable contributes importantly to the explanatory power of both the additive and multiplicative models. Second, he concluded that the multiplicative model gave better results because the requirement to estimate the Z value is eliminated (10:71).

Joseph W. Noah. Noah studied the A-7 and F-4 airframe production costs, and conducted an analysis of all major airframe cost elements. However, only the statistical analysis of production rate effects on direct labor hours is presented here (9:4).

The model he used is four-dimensional, but since it includes a production rate variable, it is of interest to this research. His model was $Y = e^A X_1^B X_2^C X_3^D$ where:

Y represents the average direct labor hours per pound of airframe produced for each airframe lot,

X_1 represents the cumulative output expressed as pounds of airframe produced through the midpoint of each successive airframe lot,

X_2 represents the production rate expressed as the average pounds of airframe delivered per month between the first and last delivery of the lot,

X_3 represents the total airframe pounds ordered for the year,

e is the base of the natural logarithm, and

A, B, C, and D are regression coefficients (9:33).

Noah used a log-transformed version of his model to regress A-7 and F-4 data and obtained R^2 values of .80 and .99, respectively (9:33). He reported that statistical analysis revealed the contribution of the production rate to be significant in each relationship examined (9:41).

To apply his model beyond the A-7 and F-4 data, he formulated a generalized model by averaging the regression coefficients (B, C, and D) obtained for the two programs. He used this generalized model to predict labor requirements for a follow-on lot of F-14 airframes which, at the time of his report, were not yet produced (9:86).

Since actual data corresponding to the F-14 predicted values were not available, the accuracy of the prediction could not be examined. However, the averaging of regression coefficients based upon the analysis of only two programs is questionable. This is particularly so, since the corresponding coefficients between the

programs were considerably different: 21 percent difference for the B coefficients, 51 percent for C coefficients, and of the opposite algebraic sign for D coefficients (9:86).

Larry L. Smith. Smith's objective was to develop and test a procedure to consider the effect of a production rate change on the direct production labor requirements to produce additional airframes within the same program (11:3). He also clearly indicated that:

> One purpose of this research is to develop a model form and define variables so that model parameters can be tailored to a continuing airframe production program. These tailored models would then be used to predict the direct labor costs of additional airframes [11:56].

He further stated that "there is no intent to develop a generalized model, only a generalized approach to building tailored cost models [11:57]." Specifically, he wanted to develop a single cost model form that could be tailored to any given program, but he did not consider a generalization of model coefficients between programs to be appropriate. Furthermore, within each program the coefficients should be updated as additional production data become available.

The model Smith chose was a modified version of Orsini's multiplicative model. The modified version was

$Y_i = B_0 \cdot X_{1i}^{B_1} \cdot X_{2i}^{B_2} \cdot 10^{\varepsilon_i}$ where:

Y_i represents the unit average direct labor hours required to output each pound of airframe in lot i,

X_{1i} represents the cumulative output of all airframes of the same type through lot i,

X_{2i} represents the lot i production rate for all airframes of the same type, and

ε_i represents the variation[3] in each dependent variable value that is not explained by the two independent variables, and

B_0, B_1, B_2 are regression coefficients (11:43).

He defends this model choice with the following reasons:

> Other writers have suggested that it might be a good predictor in this application. Multiple regression analysis is facilitated by this choice. Finally, investigation of some test data indicates that it works well [11:43].

His reference to facilitating multiple regression stems from the fact that while the model was curvilinear in its natural form, it could be linearized by taking the logarithm of all terms. The resulting transformed model

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[3] ε_i is a statistical error term that accounts for differences between observed values and those predicted by the model. When the model is used to predict values within or beyond the historical data, the 10^{ε_i} term is omitted from the model (11:43 and 4:23-27).

was $\text{Log } Y_i = \text{Log } B_0 + B_1 \text{ Log } X_{1i} + B_2 \text{ Log } X_{2i} + \epsilon_i$. When expressed in this form, multiple linear regression was possible (11:45).

Within this model, Smith used two methods to calculate a proxy for the production rate variable. The first he called a "lot average manufacturing rate" which he defined as the number of airframes in a lot divided by the lot time span. The lot time span is the time between the lot release date for the first airframe and the completion date for the last airframe. He defined the second production rate proxy as the lot "delivery rate" which is the actual monthly airframe acceptance rate (11:11-13).

As a means of isolating the production rate's contribution to the explanatory ability of the model, he also made use of a form of the standard model, $Y_i = B_0 \cdot X_{1i}^{B_1} \cdot 10^{\epsilon_i}$, where the symbols have the same meaning as in his 3-D model. He referred to this second model as the "reduced" model, and described his 3-D model as a "full" model (11:69). By regressing historical production data with each model, and comparing the statistical results, he identified the contribution of each independent variable.

In addition to determining how well the full and reduced models fit the data, Smith also conducted predictive ability tests for each model. The procedure was to: (1) omit a portion of downstream data, (2) regress each model against the remaining data to obtain model coefficients, (3) predict downstream values using the coefficients obtained, and (4) compare the predicted values with the actual values in the production data (11:56). He did not develop statistical analysis for the predictive ability tests, but instead used subjective analysis. He considered the predictive ability to be good if the model's prediction did not deviate from observed values by more than an arbitrarily chosen five percent (11:96). Furthermore, since the primary use for his model was to predict labor requirements as an aid to negotiating contract revisions for a subsequent year's production, he was mainly concerned with each model's predictive ability for one year into the future. So, although he tested each model's predictive ability for time spans exceeding one year, he was not particularly concerned with results beyond the one year time frame (11:56).

When the data provided by the manufacturers permitted, Smith evaluated fabrication and assembly labor

hours by segregating data into fabrication and assembly categories. This was possible with the F-4 and KC-135 data, but not with the F-102. In addition, since the F-4B through F-4F airframes were significant modifications of the F-4A airframe, the data for these different airframe types were at times separated and treated as two production programs (11:60,75).

In total, Smith set up 16 test situations for regression analysis and conducted predictive ability tests for most of these situations. Regression analysis and predictive ability test results are summarized in Tables 3 and 4, respectively. In Table 4 the test situations are identical to those described in Table 3 and the results presented are limited to one year predictions.

The conclusions drawn by Smith were as follows:

1. Production rate was correlated negatively and importantly with unit labor hour requirements.

2. "Lot average manufacturing rate" gave better results as a proxy for production rate than did the "delivery rate." However, both proxies contributed importantly to the full model's explanatory power.

3. The full model fit the data better than the reduced model, as evidenced by the R^2 values.

Table 3

Summary of Smith's Regression Analysis

Test Situation Number	Airframe Type	Data Points	Labor Hour Category	Production Rate Proxy	R_f^2 (actual)	R_r^2 (actual)	B_0	B_1	B_2
1	F-4A-F	57	Total	Deli	0.978	0.928	masked[a]	-0.261	-0.169
2	F-4B-F	55	Total	Manu	0.973	0.904	"	-0.246	-0.183
3	F-4B-F	55	Total	Deli	0.966	0.904	"	-0.257	-0.161
4	F-4B-F	42	Total	Manu	0.853	0.585	"	-0.230	-0.157
5	F-4B-F	42	Total	Deli	0.820	0.585	"	-0.229	-0.136
6	F-4B-F	42	Fabri	Manu	0.889	0.618	6.328	-0.221	-0.148
7	F-4B-F	42	Fabri	Deli	0.851	0.618	7.601	-0.219	-0.127
8	F-4B-F	42	Assem	Manu	0.744	0.658	9.016	-0.279	-0.112
9	F-4B-F	42	Assem	Deli	0.733	0.658	10.400	-0.278	-0.097
10	F-102A	50	Total	Deli	0.979	0.961	38.371	-0.299	-0.158
11	F-102A	42	Total	Deli	0.979	0.959	47.290	-0.344	-0.144
12	KC-135A	96	Total	Deli	0.958	0.971	13.133	-0.453	0.164
13	KC-135A	7	Fabri	Manu	0.974	0.903	0.674	-0.165	-0.305
14	KC-135A	7	Fabri	Deli	0.971	0.903	1.123	-0.233	-0.222
15	KC-135A	7	Assem	Manu	0.994	0.964	13.338	-0.608	0.361
16	KC-135A	7	Assem	Deli	0.992	0.964	7.303	-0.527	0.263

[a]The total production hours per pound were considered proprietary by the manufacturer, and these coefficients were masked in the published version of Smith's research (11:65).

Source: (11:143)

Table 4

Summary of Smith's Predictive Ability Tests

Test Situation #	% Error In Predicted Value	
	Full Model	Reduced Model
1	-2.63	14.5
2	2.23	13.6
3	Not Reported	13.6
4	2.24	5.26
5	3.07	5.26
6	-7.84	Not reported
7	"a"	Not reported
8	-0.67	1.07
9	-4.16	1.07
10	-1.05	5.61
11	3.51	Not reported
12	4.5	-3.3
13	"b"	"b"
14	"b"	"b"
15	"b"	"b"
16	"b"	"b"

[a]Smith reported the deviation was greater than that for test 6, but did not indicate the exact value (11:94).

[b]Smith reported that not enough data points were available for meaningful predictive ability tests (11:131).

Source: (11:71-125).

4. The full model explained fabrication labor hour variations more fully than assembly labor hour variations.

5. The production rate variable stabilized and improved the predictive ability of the full model for the F-4 and F-102 programs, but tests for the KC-135 were either impractical for lack of sufficient data points or inconclusive for the test situation containing sufficient data points.

6. Trying to formulate a generalized cost model from results from the F-4, F-102, and KC-135 data should not be attempted since the model coefficients varied significantly (11:142-146).

Summary

The main theme of the literature review in this chapter is that production rate is an important explainer of variations in the direct labor hours required to produce airframes. More specifically, models containing both cumulative output and production rate variables were able to explain more of the variation in direct labor requirements than models with only a cumulative output variable. Based upon these findings, further investigation

of production rate effects is justified. In particular, Smith's model and findings are worthy of further validation.

Chapter 3

RESEARCH METHODOLOGY

This chapter outlines the procedures used and research hypotheses tested. Except for minor deviations, which are discussed as they arise, the hypotheses and procedures outlined are the same as Smith's. For ease of reference the chapter is divided into six major sections:

1. Objectives and approach,
2. Variable relationships,
3. Model definitions and assumptions,
4. Research hypotheses,
5. Data collection and manipulation,
6. Summary of methodology, assumptions and limitations.

OBJECTIVES AND APPROACH

The prime objective of this study was to identify the impact on direct labor requirements resulting from externally caused production rate changes in an ongoing production program. In accomplishing this objective, a second objective of further validating Smith's model was concurrently achieved.

The approach was to collect historical production data from the T-38/F-5 program and evaluate it by replicating Smith's approach. As in his research, no attempt was made to formulate a generalized cost model. The intent was to evaluate the T-38/F-5 production data as a means of tailoring a labor hour prediction model to a specific program. Therefore, a comparison of regression coefficients obtained for the T-38/F-5 program and those obtained by Smith was of casual interest only. The ultimate value of the tailored model was a function of its ability to predict labor requirements for production of additional airframes.

VARIABLE RELATIONSHIPS

Three airframe production variables and their relationships were investigated. The variables were assumed to be continuous and were identified as follows: (1) direct labor man-hours per pound of airframe produced, (2) the cumulative number of airframes produced, and (3) the airframe production rate. Although any one of these three variables could be treated as dependent on the other two, direct labor man-hours was treated as the dependent variable. This was reasonable since both the

cumulative output and the production rate are subject to control through contractual agreement and management policy.

<u>The Labor Hours Variable</u>

The dependent variable was expressed in three categories: (1) total, (2) assembly, and (3) fabrication. When expressed as total direct labor hours, it included all the hours required by the contractor and major subcontractors to fabricate parts, assemble components from the parts, assemble the airframe from the components and to install components such as avionics and engines. It did not include the labor to produce the avionics, engines, raw materials, and bench stock items such as rivets and standard fasteners (11:38). Each labor hour category was subjected to regression analysis and predictive ability tests.

An important characteristic of the dependent variable is that it was expressed as a labor hour requirement <u>per pound of airframe</u>. In general, the total direct labor hours required to manufacture an airframe will increase as the airframe weight increases. Since design changes often dictate a change in total airframe weight, this form of the dependent variable was used to systematically reduce variations in total labor requirements.

This is a normal procedure which provides a common basis for comparing industry and government estimates. Specifically,

> Government and Industry planners have agreed to a Defense Contractor Planning Report (DCPR) weight that excludes the Government furnished equipment, fuel and lubricants. The DCPR weight was formerly called the Airframe Manufacturer Planning Report (AMPR) weight [11:11-12].

In this research then, the dependent variable was actually the unit average direct labor man-hours per DCPR pound of airframe in each lot produced (11:43).

The Cumulative Output Variable

Cumulative output is normally defined as the cumulative number of airframes produced at a given point in production. However, when airframes are produced in lots, production data are normally aggregated for the entire lot, and actual data to produce each airframe cannot be determined. For this reason, the cumulative output variable was expressed as one-half the lot size plus the cumulative number of airframes produced in previous lots. This lot midpoint value was used to match a corresponding lot average labor hour value as the dependent variable (11:42).

Further, in accordance with established learning curve theory, the first lot midpoint was adjusted to allow for the steep drop in the labor hours variable for the first few airframes. The adjustment factor was extracted from learning curve tables using the percent learning slope determined by regressing the standard model against the unadjusted midpoint data (2).

The Production Rate Variable

Since production rate is an abstract variable and not directly measurable, a suitable proxy had to be developed. The construction of this proxy depended upon the format and detail of production data provided by the manufacturer. Both the lot average manufacturing rate proxy and the delivery rate proxy developed by Smith were used in this research (11:41).

The lot average manufacturing rate was calculated as the number of airframes in a production lot divided by the production time span. The lot release date of the first airframe in a lot and the completion date of the last airframe in the lot defined the limits of the production time span. The lot release date was defined as the date work orders were issued to fabricate the first batch of parts in a lot. The completion date was

the date the customer accepted the last completed aircraft in a lot by signature (11:41).

The lot delivery rate was calculated by dividing the number of airframes in a lot by the time span over which airframes were delivered for that lot. This time span was the time between acceptance of the first and last aircraft in the lot. Constructing this rate required only the number of airframes in the lot and the acceptance dates (11:41).

MODEL DEFINITION AND ASSUMPTIONS

As discussed in Chapter 2, Smith examined two models which he labeled as the "reduced model" and the "full model." They are reiterated here for ease of reference.

Model Definition

The reduced model is a form of the standard learning curve model where:

$$Y_i = B_0 \cdot X_{1i}^{B_1} \cdot 10^{\epsilon_i} \ .$$

The full model includes a second independent variable for production rate where:

$$Y_i = B_0 \cdot X_{1i}^{B_1} \cdot X_{2i}^{B_2} \cdot 10^{\epsilon_i} .$$

Common terms in each model have the same meaning and are described as follows:

Y_i represents the unit average direct labor hours required to output each pound of airframe in lot i,

X_{1i} represents the cumulative output of all airframes of the same type through lot i,

X_{2i} represents the lot i production rate for all airframes of the same type,

ϵ_i represents the variation in each dependent variable value that is not explained by the two independent variables, and

B_0, B_1 and B_2 are regression coefficients (11:42).

Model Evaluation Assumptions

Least squares multiple linear regression was used to analyze each model. To facilitate regression analysis, the models were transformed to a linear form by taking the logarithm of each term. These transformed models are also reiterated. In log-linear form the reduced model is

$$\text{Log } Y_i = \text{Log } B_0 + B_1 \text{ Log } X_{1i} + \epsilon_i$$

and the full model is

$$\text{Log } Y_i = \text{Log } B_0 + B_1 \text{ Log } X_{1i} + B_2 \text{ Log } X_{2i} + \epsilon_i .$$

To permit statistical significance testing on the regression results, the error terms in the logarithm domain were assumed to be normally distributed with a

mean of zero and a constant variance. Further, the error terms were assumed to be independent of each other and of the independent variables.

A problem with regression analysis in this situation is that multi-collinearity between the two independent variables will probably occur. Support for this possibility is taken from the basic learning curve theory stated in reverse. Specifically, if available labor hours are held constant while cumulative output increases, the rate of production should increase because each successive item requires less labor production time.

When high multi-collinearity exists between independent variables in regression analysis, the standard error of the estimate of the individual regression coefficients may become unreliably large (11:46). One result of this might be to reject the significance of the coefficients when, in fact, they are significant. While multi-collinearity may cause statistical significance tests to fail, the predictive ability of the model may not be impaired. Since predictive ability is the ultimate test of the model, the production rate's contribution to the model can still be subjectively evaluated by comparing predictions, made with the full and reduced models, against each other and against the observed values.

RESEARCH HYPOTHESES

The three research hypotheses tested by Smith were also tested in this research. The first stated that "production rate is an important explainer of variation in total direct labor requirements when included in an appropriate model [11:48]." For purposes of continuity, Smith's second hypothesis was reworded as follows: Production rate is an important explainer of variation in direct fabrication labor requirements and direct assembly labor requirements when included in an appropriate model (11:47). His third hypothesis stated that "the predictive ability of each (full) model is good for one year into the future [11:56]."

Research Hypothesis One (11:48-54)

The first research hypothesis was tested indirectly by performing statistical significance and subjective criteria tests on model coefficients determined by regression of historical airframe production data. The model tested was the full model expressed in logarithmic form.

In testing this hypothesis, the dependent variable subjected to regression analysis was the logarithm of total direct hours per pound. The independent variables

were the logarithms of the cumulative output at the production lot midpoint and the production rate. Both of the defined forms of the production rate were examined.

Statistical Hypothesis one (A) (11:48-49). This hypothesis states that cumulative production and production rate are related to hours per pound as indicated in the model. When expressed in null and alternate hypothesis form it becomes:

$$H_o: \; B_1 \text{ and } B_2 = 0$$

$$H_a: \; B_1 \neq 0 \text{ and/or } B_2 \neq 0 .$$

The null hypothesis was rejected and the alternate hypothesis accepted when the test statistic F^* was greater than the critical statistic F_c at the 0.05 level of significance.[1] For this test[2], $F^* = [EV/(p-1)] \div [UV/(n-p)]$ where:

EV represents the explained variation and is defined as the sum of the square of differences between logarithms of the predicted dependent variable values and the mean of the observed dependent variable values,

---

[1]The F_c values were extracted from an F-distribution table (8:807-813).

[2]Although Smith used different symbology, the F^* calculation method used here is equivalent to his.

UV represents the unexplained variation and is defined as the sum of the squared differences between logarithms of the observed dependent variable values and the corresponding predicted values,

n is the number of observations, and

p is the number of coefficients estimated during regression (4:22).

<u>Statistical hypothesis one (B)</u> (11:49-50). This hypothesis was formulated to test the ability of the production rate variable, when combined with the cumulative output variable, to explain additional variation in the direct labor hours. In statistical terms, this is equivalent to stating that the B_2 coefficient has a non-zero value at a prespecified level of significance. The hypothesis is stated in null and alternate form as follows:

$$H_o: \; B_2 = 0$$

$$H_a: \; B_2 \neq 0$$

Again, the null hypothesis was rejected when the test statistic F^* was greater than the critical statistic F_c at the 0.05 level of significance.

For this test, F^* was calculated by determining the increase in explained variation of the dependent variable that could be attributed to adding the production rate variable to the reduced model. Specifically,

$F^{*} = [\Delta EV] \div [UV/(n-p)]$, which is equivalent to

$F^{*} = [(R_f^2 - R_r^2)TV] \div [UV/(n-p)]$, where:

> ΔEV represents the change in explained variation resulting from the introduction of the logarithm of the production rate variable,
>
> R_f^2 is the coefficient of determination for the full model and is the ratio of EV_f/TV, and
>
> R_r^2 is the coefficient of determination for the reduced model and equals EV_r/TV (11:31).

Criterion test (11:50-54). Smith formulated a third statistical hypothesis to evaluate the overall appropriateness of the full model. However, he did not perform statistical significance tests to evaluate the hypothesis. This inconsistency in methodology did not affect the validity of Smith's analysis, but from a research theory standpoint, a criterion test was more appropriate than a hypothesis test. So, although a criterion test was used here, the method of analysis was the same as Smith's.

A formal statement of this criterion test is: When the full model explained more of the variation in direct labor hours than the reduced model, and when an examination of residuals revealed that the assumptions on error terms were not violated, the model was appropriate. More specifically, the model's appropriateness could not be rejected when: (1) the subjective tests

described in the following paragraphs did not reveal a substantial departure from the assumptions of constant residual variance, residual independence, and normal distribution of residuals; (2) the R^2 value for the full model was greater than the R^2 value for the reduced model.

The assumption that residual variance is constant was checked by plotting the residual values against the dependent variable values predicted by the regressed model. When the plot pattern revealed that residuals were evenly distributed over the range of observations, and the bulk of residuals were within one standard error of the estimate, the assumption of constant residual variance was considered to be valid (11:51).

That residuals were independent of each other and independent of the independent variables was examined by plotting residual values against each independent variable. When no cyclic recurrences or trends could be identified, and when the residuals fluctuated randomly above and below the line formed by the predicted values, the assumption of independence was considered valid (11:51).

A means of checking for a normal distribution of residuals was to plot them as a frequency distribution on normal probability paper. When the distribution did not deviate substantially from a straight line, the assumption of normality was considered to be valid (11:52).

Examination of R^2 values for the full and reduced model was appropriate since two forms of R^2 existed as a result of log-linearizing the models prior to performing the regression analysis. The two forms are symbolized as follows: (1) R_f^2 (log) for the coefficient of determination of the full model in the logarithm domain, and (2) R_f^2 (actual) for the full model in its natural form. R_r^2 (log) and R_r^2 (actual) are similarly defined for the reduced model.

Evaluation of R_r^2 (log) and R_f^2 (log) was not made since Statistical Hypothesis One (A) was equivalent to performing significance tests on R_f^2 (log) (4:31). For the purpose of evaluating the criterion test, attention was focused on R_f^2 (actual) and R_r^2 (actual).

The R^2 (actual) terms were determined by computing and comparing the regression model's prediction of each actual direct labor hour value with the actual observed value. The EV and TV statistics were then calculated in

the same manner as explained earlier for the logarithmic values. The resulting values of R_f^2 (actual) and R_r^2 (actual) were then compared (11:52).

<u>Research hypothesis one test summary</u>. When the null hypothesis in Statistical Hypotheses One (A) and (B) were both rejected, and the conditions specified in the criterion test were not violated, the full model was accepted as an appropriate modification to the reduced model. When the model was accepted, it followed that the production rate contributed importantly to the explanation of variation in total direct labor hours required to produce an airframe.

<u>Research Hypothesis Two</u> (11:54-55)

The only difference between the first and second research hypotheses was that the terms <u>direct fabrication labor requirements</u> and <u>direct assembly labor requirements</u> were substituted one at a time for <u>total direct labor requirements</u>. Since this change was accommodated by revising the model's dependent variable only, the same statistical hypotheses and criterion test used to evaluate research hypothesis one were again applicable.

Research Hypothesis Three (11:56)

Since the third research hypothesis does not lend itself to formulation of a statistical subhypothesis, a criterion test for subjective analysis is presented. Specifically, the model's predictive ability was accepted as good when the one year predictions did not deviate from observed values by more than five percent (11:96).

The method for evaluating predictive ability of the model was explained by Smith as follows:

> In a real application of the model, the prediction would be beyond the range of the historical data. The only way to test the accuracy of the prediction would be to wait and see how many hours it takes to build the next airframe lot. To simulate this situation, the regression coefficients in the model are estimated with the last few observed data points omitted. Then using this new model, omitted values (which are known but not used in estimating the model coefficients) are predicted. Comparisons are then drawn between the actual and predicted hours as a subjective measure of predictive ability [11:56].

DATA COLLECTION

Since the research approach was to tailor Smith's full model to a set of production data, and not to generalize the model for all production programs, accessibility was the primary basis for data selection.

With the exception of aircraft acceptance dates, the T-38/F-5 data were obtained directly from the

manufacturer. These dates were obtained from Aircraft Accountability Records (AFLC Form 1026) at Air Force Logistics Command Headquarters (AFLC/LOAC-AVDO) for airframes delivered after November 1961. Prior acceptance date information was destroyed by fire and had to be estimated from delivery schedule information provided by the manufacturer.

Two problems with using the delivery schedule dates arose. First, the schedule gave dates by month and year only. To minimize the error related to this problem, the actual delivery date was assumed to have been on the 15th day of the scheduled month.

The second problem was that these schedules reflected the delivery months called for by contract, but were not necessarily the actual delivery months. To determine the extent of this problem, a comparison of actual acceptance dates with delivery schedule dates for airframes delivered after November 1961 was made. Since this comparison revealed very few discrepancies, the delivery schedule dates were, therefore, assumed to be acceptable substitutes for the actual acceptance dates for airframes delivered from the first eight lots of T-38 data.

Another assumption that relates to the entire data set was that data for the program were a population census and not a sample. This is true since, even though the F-5 is still in production, only historical data were analyzed. In this context, the statistics derived were direct descriptions of the population within the limits of the model's explanatory power and the research methodology. No generalization of model coefficients, beyond the program for which the model is tailored, was attempted.

SUMMARY OF METHODOLOGY, ASSUMPTIONS, AND LIMITATIONS

The approach analyzed historical production data using multiple linear regression analysis. Statistical and criteria tests were established to evaluate the efficiency of Smith's model as an explainer of variations in direct labor hour requirements for airframe production. Additional procedures and associated criteria tests were outlined to test the predictive ability of his model. When all statistical and criteria tests were met, the conclusion that production rate was an important contributor to explaining direct labor hour variations was supported. Finally, the conclusion that Smith's full model is an appropriate modification to the standard learning curve model was supported.

The strength and validity of these conclusions were evaluated in terms of the assumptions and limitations inherent in the methodology. With that in mind, a recap of these assumptions and limitations is provided.

Assumptions

Historical data obtained from the manufacturer were accurate.

The data were accurately measured and manipulated; particularly for lot midpoint and production rate calculations.

Logarithmic transformation of data to facilitate multiple linear regression introduced no significant loss of data precision.

Limitations

Subjective analysis was required to assess validity of error term assumptions.

Limited number of data points resulted in reduction of statistical "leverage" (i.e., limited degrees of freedom in statistical tests) in some instances.

The extent of error introduced by estimating the actual acceptance dates from delivery schedules for the first eight lots of T-38 airframes cannot be fully ascertained.

Chapter 4

DATA ANALYSIS AND FINDINGS

The two basic functions of this chapter are to describe the T-38/F-5 data, obtained from the manufacturer, and to present the results and findings obtained from their analysis. The intent is to present this information with directness and as little bias and prejudice as possible. With this in mind, tabular presentations are used whenever possible. For the same reason, discussions are limited to the minimum necessary to describe the format of the various tables and to indicate what was done to arrive at the tabulated information. The verbal summaries provided at the end of each section and at the end of the chapter are designed to merely recap the important findings with few or no "real-world" interpretations. Such interpretations are reserved for discussion in Chapter 5.

This chapter is divided into six sections. The first provides a description of the data, the next three present analyses of the data relative to each research hypothesis, the fifth presents a finding related to all three research hypotheses, and the final section provides an overall summary of the analyses.

T-38/F-5 DATA DESCRIPTION

With the exception of the aircraft acceptance dates discussed in Chapter 3, the data were obtained directly from the manufacturer.[1] Specifically, the manufacturer provided labor hour, DCPR weight, inclusive tail number and fabrication release date information by production lot for each of the following airframe models: T-38, F-5A, F-5AG, RF-5A, RF-5AG, F-5B, F-5BG, and F-5E. The labor hour data were further separated into three categories: total, fabrication, and assembly. The above data were provided for all airframes built for each model except the F-5E. Since the F-5E was still in production, only five lots of data were available for this model. Table 5 summarizes the number of airframes for each model that was produced in each lot.

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[1] The manufacturer developed a single data source document, from numerous data files and records at his disposal, in support of this research. This single document is the source of all data discussed and tabulated, with the exception of aircraft acceptance dates as previously discussed.

The manufacturer considers much of the data to be proprietary. For that reason numerous table entry values have been masked in the published version of this thesis. Access to these masked values can be obtained from the authors upon written approval from Northrop Aircraft Corporation.

Table 5

Lot Composition

Lot #	T-38	F-5A	F-5B	RF-5A	RF-5AG	F-5AG	F-5BG	F-5E
1	2							
2	2							
3	4							
4	4							
5	5							
6	15							
7	16							
8	19							
9	36							
10	36							
11	36							
12	36							
13	36							
14	36							
15	36	7						
16	36	-						
17	36	7						
18	36	-	7					
19	36	12	8					
20	29	16	-					
21	47	29	-					
22	47	30	7					
23	46	32	3			9	2	
24	48	24	12			9	2	
25	48	39	-			11	-	
26	64	23	-			-	-	
27	29	33	11			12	4	
28	51	34	-			-	-	
29	46	21	-			11	-	
30	-	64	13			-	-	
31	35	31	-	13		16	4	
32	44	34	-	3		-	-	
33	69	-	8	-		-	-	
34	-	8	5	-	16	-	-	
35	54	9	-	-		-	-	
36	-	15	2	16		-	-	
37	16	19	-	-		-	-	
38	-	-	-	21		10	2	

Table 5 (Continued)

Lot #	T-38	F-5A	F-5B	RF-5A	RF-5AG	F-5AG	F-5BG	F-5E
39	20	39	-	-				
40	23	-	8	9				
41	8	17	-	-				
42[a]			-	-				
43			2	11				
44			14					5
45			20					21
46			10					12
47								62
48								62

[a]Lot 42 was used for production of items that were common to all airframes still in production. The labor hours consumed in this lot were assigned to airframes actually produced in subsequent lots.

Data Accommodation

One characteristic of the data set that is not accommodated by the learning curve models is the extensive design change between the F-5B and F-5E. This change is reflected in the data set by an approximate 15 percent increase in DCPR weight for the F-5E and by an abrupt 475 percent increase in total labor hours per pound for the first lot of F-5E airframes. Preliminary regression analysis with the five F-5E lots included in the data set vividly revealed the inability of the model to account for this drastic labor hour variation. Based on this preliminary finding, the data from lots 44 through 48 were omitted from the analysis presented for hypothesis testing in the next three sections of this chapter. While this omission of data may seem arbitrary, the reader is reminded that the primary thrust of this and Smith's research was to determine if his model could be adapted to the production of an ongoing program. In his words, "frequent engineering changes seem to be dynamically accommodated as long as the changes are not major [11:9]." Support for this statement is shown in later sections, where the relatively minor changes between the other airframe models presented no particular problem.

Data Combinations

As indicated earlier in Table 5, extensive overlap and simultaneous production of different models occurred during the majority of the T-38/F-5 program. Because of these multi-model production lots, data for various combinations of airframe models were evaluated against the three research hypotheses. After preliminary analysis of more than a dozen combinations, five were selected as showing promise for futher analysis.

The data combinations are referred to as test situations, and actual regression analysis input data for each combination is tabulated in Appendix A. Table 6 provides a synopsis of the data contained in each test situation, and the following discussion is keyed to this table.

In general, each test situation number represents the combination of airframe models used to generate the variables for regression analysis and predictive ability testing. For each combination, each labor hour category and each production rate proxy was analyzed.

The second table column indicates the range of lots from which the data were extracted. To avoid confusion in later discussions, note in Table 5 that some lots were skipped in the production sequence of

Table 6

Regression Analysis Test Situations Summarized

Test Situation #, Labor Hr. Category, & Prod. Rate Proxy	Production Lot Numbers Included	Labor Hours Variable (Y) Based on:	Cumulative Output (X_1) Based on:	Production Rate (X_2) Based on:
1TM/1TD[a]	1 - 43	All Models	All Models	All Models
1FM/1FD[a]	1 - 43	All Models	All Models	All Models
1AM/1AD[a]	1 - 43	All Models	All Models	All Models
2TM/2TD	1 - 43	T-38/Basic F-5[b]	All Models	All Models
2FM/2FD	1 - 43	T-38/Basic F-5[b]	All Models	All Models
2AM/2AD	1 - 43	T-38/Basic F-5[b]	All Models	All Models
3TM/3TD	1 - 41	T-38 Only	T-38 Only	T-38 Only
3FM/3FD	1 - 41	T-38 Only	T-38 Only	T-38 Only
3AM/3AD	1 - 41	T-38 Only	T-38 Only	T-38 Only
4TM/4TD	15 - 43	All F-5[c]	All F-5	All F-5
4FM/4FD	15 - 43	All F-5[c]	All F-5	All F-5
4AM/4AD	15 - 43	All F-5[c]	All F-5	All F-5
5TM/5TD	15 - 43	Basic F-5	Basic F-5	Basic F-5
5FM/5FD	15 - 43	Basic F-5	Basic F-5	Basic F-5
5AM/5AD	15 - 43	Basic F-5	Basic F-5	Basic F-5

[a]Key to symbols: Total labor hours--"T"; Fabrication labor hours--"F"; Assembly labor hours--"A"; Manufacturing rate--"M"; and Delivery rate--"D".

[b]"Basic F-5" includes the F-5A and F-5B models only.

[c]"All F-5" includes the basic F-5 models plus the F-5AG, RF-5A, RF-5AG, and F-5BG.

each airframe model. The number of cases (data plot points) used in the regression analysis of each test situation was, therefore, usually less than the inclusive number of lots in the range.

The Labor Hours Variable column reflects the airframe model or models for which labor data were compiled. For example, the designation of "T-38/Basic F-5" refers to all T-38 airframes produced plus the basic F-5 airframes. Specifically, the T-38, F-5A, and F-5B labor hours were included, but the labor hours for the F-5AG, RF-5A, RF-5AG, and F-5BG were excluded. This omission of the special models in Test Situation 2 closely approximates Smith's similar attempt to develop a homogeneous data set in portions of his research (11:60-61).

The Cumulative Output column of the table indicates which airframe models were used to calculate the cumulative output variable for regression. Output for all airframe models was used in Test Situations 1 and 2 in order to evaluate direct labor requirements as a function of the production of all airframe models. The great similarity between models implied that much of the learning that took place in producing one model was applicable to the production of other models. In Test

Situations 3, 4, and 5, however, an attempt was made to isolate the learning achieved on the T-38 models from that achieved on the F-5 models and vice-versa. In these situations, the cumulative output variable was based on the cumulative output of the indicated models only. As a point of clarification, Smith did not examine data combinations equivalent to those in Test Situations 3, 4, and 5.

The Production Rate column indicates the portion of airframes in each lot, by airframe model, that was included in the development of the manufacturing rate and delivery rate variables. The designation "all models" for Test Situations 1 and 2 reflects a plant-wide rate of production for all models produced in each lot under consideration. As was the case for cumulative output, the similarity between airframe models makes this plant-wide production rate seem logically appropriate for evaluation. Again, however, in the remaining test situations an attempt was made to isolate the effects of production rate of certain models within each lot. For instance, Test Situation 3 used only the number of T-38 airframes produced in each lot to determine the production rate. Additionally, the manufacturing rate and delivery rate time span calculations explained in

Chapter 3 were based solely on T-38 airframe acceptance dates and fabrication release dates.

RESEARCH HYPOTHESIS ONE ANALYSIS

This section presents the regression analysis results for Test Situations 1 through 5 as they relate to each statistical hypothesis and the criterion test used to support this research hypothesis. For ease of reference, the hypotheses and criterion test are reiterated in summary form as follows:

Research Hypothesis One: Production rate, when included in an appropriate model, is an important explainer of variation in total direct labor hour requirements.

Statistical Hypothesis One (A): H_o: B_1 and $B_2 = 0$; H_a: $B_1 \neq 0$ and/or $B_2 \neq 0$. Reject H_o if $F^* > F_c$.

Statistical Hypothesis One (B): H_o: $B_2 \neq 0$; H_a: $B_2 \neq 0$ Reject H_o if $F^* > F_c$.

Criterion Test: The model's appropriateness cannot be rejected if: (1) the assumptions of constant residual variance, residual independence and normal residual distribution are not violated, and (2) the R^2 value for the full model is greater than the R^2 value of the reduced model.

The results obtained for each test situation are individually tabulated in the remainder of this section. As an aid to interpreting the tabular format, note that reduced model results are the same regardless of the production rate variable proxy used in the full model.

Test Situations 1TM/1TD Analysis Results

For these tests the total labor hours for all lots and all models were regressed against the cumulative output for all models and the plant-wide production rate. The regression results and hypothesis test conclusions are summarized in Table 7. The regression input data are presented in Appendix A, Table 19.

Table 7

Test Situations 1TM/1TD: Regression Results and Conclusions

Items of Concern	Reduced Model	Full Model	
	1TM/1TD	1TM	1TD
Number of Cases	42	42	42
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.938	0.987	0.971
R^2 (log)	0.934	0.985	0.970
F^* (B_1, $B_2 \neq 0$)	—	1295.78	627.53
F_c (B_1, $B_2 \neq 0$)	—	3.24	3.24
Stat. Hyp. One (A)	—	Reject H_0	Reject H_0
F^* ($B_2 \neq 0$)	—	135.39	46.79
F_c ($B_2 \neq 0$)	—	4.08	4.08
Stat. Hyp. One (B)	—	Reject H_0	Reject H_0
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Test Situations 2TM/2TD Analysis Results

For these tests total labor hours for the T-38, F-5A, and F-5B only were regressed against the cumulative output and the plant-wide production rate for all models. Results are summarized in Table 8 and input data are in Appendix A, Table 20.

Table 8

Test Situations 2TM/2TD: Regression Results and Conclusions

Item of Concern	Reduced Model	Full Model	
	2TM/2TD	2TM	2TD
Number of Cases	41	41	41
B_0	masked	masked	masked
B_1	masked	masked	masked
B_2	—	masked	masked
R^2 (actual)	0.943	0.987	0.973
R^2 (log)	0.938	0.986	0.972
F^* (B_1, $B_2 \neq 0$)	—	1311.63	669.90
F_c (B_1, $B_2 \neq 0$)	—	3.25	3.25
Stat. Hyp. One (A)	—	Reject H_o	Reject H_o
F^* ($B_2 \neq 0$)	—	125.70	46.75
F_c ($B_2 \neq 0$)	—	4.10	4.10
Stat. Hyp. One (B)	—	Reject H_o	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Test Situations 3TM/3TD Analysis Results

In these tests total labor hours for the T-38 only were regressed against the T-38 cumulative output and the portion of the plant-wide production rate in each lot that could be attributed to T-38 production. Results are summarized in Table 9 and the input data are presented in Appendix A, Table 21.

Table 9

Test Situations 3TM/3TD: Regression Results and Conclusions

Items of Concern	Reduced Model	Full Model	
	3TM/3TD	3TM	3TD
Number of Cases	37	37	37
B_0	masked	masked	masked
B_1	masked	masked	masked
B_2	—	masked	masked
R^2 (actual)	0.979	0.988	0.990
R^2 (log)	0.972	0.991	0.987
F^* $(B_1, B_2 \neq 0)$	—	1774.47	1287.41
F_c $(B_1, B_2 \neq 0)$	—	3.28	3.28
Stat. Hyp. One (A)	—	Reject H_o	Reject H_o
F^* $(B_2 \neq 0)$	—	64.91	38.01
F_c $(B_2 \neq 0)$	—	4.13	4.13
Stat. Hyp. One (B)	—	Reject H_o	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Test Simulations 4TM/4TD Analysis Results

For these tests total labor hours for all F-5 models were regressed against the cumulative output for all F-5 models and the portion of the plant-wide production rate attributable to all F-5 models. Results are summarized in Table 10 and the input data are presented in Appendix A, Table 22.

Table 10

Test Situations 4TM/4TD: Regression Results and Conclusions

Items of Concern	Reduced Model	Full Model	
	4TM/4TD	4TM	4TD
Number of Cases	27	27	27
B_0	masked	masked	masked
B_1	masked	masked	masked
B_2	—	masked	masked
R^2 (actual)	0.891	0.933	0.947
R^2 (log)	0.896	0.942	0.934
F^* (B_1, $B_2 \neq 0$)	—	193.61	171.08
F_c (B_1, $B_2 \neq 0$)	—	3.40	3.40
Stat. Hyp. One (A)	—	Reject H_o	Reject H_o
F^* ($B_2 \neq 0$)	—	18.81	14.12
F_c ($B_2 \neq 0$)	—	4.26	4.26
Stat. Hyp. One (B)	—	Reject H_o	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Test Situations 5TM/5TD Analysis Results

These were the last tests using total labor hours as the dependent variable. Specifically, total labor hours for basic F-5 models only were regressed against basic F-5 cumulative output and the portion of the plant-wide production rate attributable to these basic models. Results are summarized in Table 11 and input data are presented in Appendix A, Table 23.

Table 11

Test Situations 5TM/5TD: Regression Results and Conclusions

Items of Concern	Reduced Model	Full Model	
	5TM/5TD	5TM	5TD
Number of Cases	26	26	26
B_0	masked	masked	masked
B_1	masked	masked	masked
B_2	—	masked	masked
R^2 (actual)	0.903	0.939	0.975
R^2 (log)	0.909	0.950	0.957
F^* (B_1, $B_2 \neq 0$)	—	177.14	254.13
F_c (B_1, $B_2 \neq 0$)	—	3.42	3.42
Stat. Hyp. One (A)	—	Reject H_o	Reject H_o
F^* ($B_2 \neq 0$)	—	13.77	28.77
F_c ($B_2 \neq 0$)	—	4.28	4.28
Stat. Hyp. One (B)	—	Reject H_o	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Research Hypothesis One Analysis Summary

For this research hypothesis the two statistical hypotheses and the criterion test concerning total labor hour variations were evaluated. Within the framework of the five basic test situations, the impact of production rate was analyzed using both the manufacturing rate and the delivery rate proxies.

In every situation tested the full model showed very strong overall significance under Statistical Hypothesis One (A). This was evidenced by the overwhelming size of F^* statistics when compared to F_c statistics and was similarly shown by the very high R^2 (actual) values. In the worst situation (1TM) the full model explained 93.3 percent of the variations in the labor hours variable, and in the best situation (3TD) it explained 99.0 percent of the variation. More importantly, the full model explained approximately four percent more of the variation than did the reduced model in all situations except 3TM and 3TD where the increase was only about one percent. The significance of these increases is emphasized in the following discussion of findings for the production rate variable.

The production rate variable was shown to have a statistically significant relationship with variations

in the total labor hour variable. The strength of this relationship was evidenced by the fact that F^* statistics under Statistical Hypothesis One (B) were considerably larger than the F_c statistics in each situation tested. The smallest margin of difference between F^* and F_c occurred in Test Situation 5TM where F^* was 13.77 and F_c was 4.28 at the 0.05 level of significance. However, even this F^* statistic is large enough to permit rejection of H_o at the 0.005 level of significance where F_c would increase to only 9.63.

While the production rate variable was found to be significant using both the manufacturing rate and the delivery rate, neither of these proxies demonstrated a clear advantage over the other. For instance, the full model with manufacturing rate gave higher R^2 values in two test situations, the same R^2 value in the third, and lower values in the last two.

Also of interest was the fact that all B_2 coefficients were negative, which implied an inverse relationship between the variables. Specifically, as the production rate variable increased, the labor hours variable decreased.

Finally, the conditions specified in the criterion test were met for all test situations. Specifically,

for each situation the R^2 value for the full model was greater than the R^2 value for the reduced model, and the assumptions concerning residuals were not violated.

RESEARCH HYPOTHESIS TWO ANALYSIS

This hypothesis is the same as Research Hypothesis One except that labor hours are examined at the lower production process levels of fabrication and assembly. Further, since the total labor hours examined previously were simply the sum of the fabrication and assembly hours examined in this section, findings for total labor hours represented the combined effect of the production rate variable on fabrication and assembly. For instance, if the production rate variable was significant for assembly hours but not for fabrication hours, the variable may still have shown significance for total combined hours. For this reason, the R^2 and F^* statistics for the total hours presented in the previous section should be kept in mind when examining the findings of this section.

Test Situations 1FM/1FD and 1AM/1AD

For these tests the fabrication labor hours and the assembly labor hours were regressed against the

cumulative output for all models and the plant-wide production rate. Results are summarized in Table 12 and input data are presented in Appendix A, Table 19.

Table 12

Test Situations 1FM/1FD and 1AM/1AD: Regression Results and Conclusions

Items of Concern	Reduced Model	Full Model	
	1FM/1FD	1FM	1FD
Number of Cases	42	42	42
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.868	0.974	0.921
R^2 (log)	0.857	0.970	0.923
F^* (B_1, $B_2 \neq 0$)	—	624.68	254.12
F_c (B_1, $B_2 \neq 0$)	—	3.24	3.24
Stat. Hyp. Two (A)	—	Reject H_0	Reject H_0
F^* ($B_2 \neq 0$)	—	144.81	39.08
F_c ($B_2 \neq 0$)	—	4.08	4.08
Stat. Hyp. Two (B)	—	Reject H_0	Reject H_0
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed
	1AM/1AD	1AM	1AD
Number of Cases	42	42	42
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.971	0.980	0.986
R^2 (log)	0.965	0.980	0.977
F^* (B_1, $B_2 \neq 0$)	—	976.11	843.29
F_c (B_1, $B_2 \neq 0$)	—	3.24	3.24
Stat. Hyp. Two (A)	—	Reject H_0	Reject H_0
F^* ($B_2 \neq 0$)	—	30.89	21.56
F_c ($B_2 \neq 0$)	—	4.08	4.08
Stat. Hyp. Two (B)	—	Reject H_0	Reject H_0
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Test Situations 2FM/2FD and 2AM/2AD

For these tests the fabrication and assembly labor hours for the T-38, F-5A, and F-5B only were regressed against the cumulative output and plant-wide production rate for all models. Results are summarized in Table 13 and input data are presented in Appendix A, Table 20.

Table 13

Test Situations 2FM/2FD and 2AM/2AD: Regression Results and Conclusions

Items of Concern	Reduced Model	Full Model	
	2FM/2FD	2FM	2FD
Number of Cases	41	41	41
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.877	0.968	0.925
R^2 (log)	0.863	0.976	0.934
F^* (B_1, $B_2 \neq 0$)	—	576.84	268.78
F_c (B_1, $B_2 \neq 0$)	—	3.25	3.25
Stat. Hyp. Two (A)	—	Reject H_o	Reject H_o
F^* ($B_2 \neq 0$)	—	124.78	40.62
F_c ($B_2 \neq 0$)	—	4.10	4.10
Stat. Hyp. Two (B)	—	Reject H_o	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed
	2AM/2AD	2AM	2AD
Number of Cases	41	41	41
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.973	0.979	0.986
R^2 (log)	0.967	0.981	0.978
F^* (B_1, $B_2 \neq 0$)	—	960.61	826.07
F_c (B_1, $B_2 \neq 0$)	—	3.25	3.25
Stat. Hyp. Two (A)	—	Reject H_o	Reject H_o
F^* ($B_2 \neq 0$)	—	25.75	17.00
F_c ($B_2 \neq 0$)	—	4.10	4.10
Stat. Hyp. Two (B)	—	Reject H_o	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Test Situations 3FM/3FD and 3AM/3AD

For these tests fabrication and assembly labor hours for the T-38 only were regressed against the T-38 cumulative output and the portion of the plant-wide production rate in each lot that was attributable to T-38 production. Results are summarized in Table 14 and input data are presented in Appendix A, Table 21.

Table 14

Test Situations 3EM/3FD and 3AM/3AD: Regression Results and Conclusions

Items of Concern	Reduced Model	Full Model	
	3EM/3FD	3EM	3FD
Number of Cases	37	37	37
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.948	0.990	0.967
R^2 (log)	0.929	0.979	0.961
F^* (B_1, $B_2 \neq 0$)	—	793.31	421.24
F_c (B_1, $B_2 \neq 0$)	—	3.28	3.28
Stat. Hyp. Two (A)	—	Reject H_o	Reject H_o
F^* ($B_2 \neq 0$)	—	81.20	28.30
F_c ($B_2 \neq 0$)	—	4.13	4.13
Stat. Hyp. Two (B)	—	Reject H_o	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed
	3AM/3AD	3AM	3AD
Number of Cases	37	37	37
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.972	0.966	0.975
R^2 (log)	0.988	0.990	0.992
F^* (B_1, $B_2 \neq 0$)	—	1751.77	2048.74
F_c (B_1, $B_2 \neq 0$)	—	3.28	3.28
Stat. Hyp. Two (A)	—	Reject H_o	Reject H_o
F^* ($B_2 \neq 0$)	—	8.01	15.07
F_c ($B_2 \neq 0$)	—	4.13	4.13
Stat. Hyp. Two (B)	—	Reject H_o	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Test Situations 4FM/4FD and 4AM/4AD

For these tests fabrication and assembly labor hours for all F-5 models were regressed against the cumulative output of all F-5 models and the portion of the plant-wide production rate attributable to these models. Results are summarized in Table 15 and input data are presented in Appendix A, Table 22.

Table 15

Test Situations 4FM/4FD and 4AM/4AD: Regression Results and Conclusions

Items of Concern	Reduced Model	Full Model	
	4FM/4FD	4FM	4FD
Number of Cases	27	27	27
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.772	0.864	0.877
R^2 (log)	0.740	0.855	0.847
F^* (B_1, $B_2 \neq 0$)	—	71.01	66.46
F_c (B_1, $B_2 \neq 0$)	—	3.40	3.40
Stat. Hyp. Two (A)	—	Reject H_0	Reject H_0
F^* ($B_2 \neq 0$)	—	19.20	16.83
F_c ($B_2 \neq 0$)	—	4.26	4.26
Stat. Hyp. Two (B)	—	Reject H_0	Reject H_0
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed
	4AM/4AD	4AM	4AD
Number of Cases	27	27	27
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.930	0.951	0.958
R^2 (log)	0.940	0.955	0.950
F^* (B_1, $B_2 \neq 0$)	—	256.49	229.69
F_c (B_1, $B_2 \neq 0$)	—	3.40	3.40
Stat. Hyp. Two (A)	—	Reject H_0	Reject H_0
F^* ($B_2 \neq 0$)	—	82.89	5.06
F_c ($B_2 \neq 0$)	—	4.26	4.26
Stat. Hyp. Two (B)	—	Reject H_0	Reject H_0
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Test Situations 5FM/5FD and 5AM/5AD

In this last set of tests the fabrication and assembly labor hours for basic F-5 models only were regressed against the basic F-5 cumulative output and the portion of the plant-wide production rate attributable to these basic models. Results are summarized in Table 16 and input data are presented in Appendix A, Table 23.

Note that under Test Situation 5FM the null hypothesis could not be rejected at the 0.05 level of significance under Statistical Hypothesis Two (B). This condition is flagged with an asterisk in Table 16 and is discussed more fully in the summary portion of this section.

Table 16

Test Situations 5FM/5FD and 5AM/5AD: Regression Results and Conclusions

Items of Concern	Reduced Model	Full Model	
	5FM/5FD	5FM	5FD
Number of cases	26	26	26
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.771	0.822	0.873
R^2 (log)	0.711	0.750	0.805
F^* (B_1, $B_2 \neq 0$)	—	34.54	47.44
F_c (B_1, $B_2 \neq 0$)	—	3.42	3.42
Stat. Hyp. Two (A)	—	Reject H_o	Reject H_o
F^* ($B_2 \neq 0$)	—	3.57	11.01
F_c ($B_2 \neq 0$)	—	4.28	4.28
Stat. Hyp. Two (B)	—	*	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed
	5AM/5AD	5AM	5AD
Number of cases	26	26	26
Estimated B_0	masked	masked	masked
Estimated B_1	masked	masked	masked
Estimated B_2	—	masked	masked
R^2 (actual)	0.947	0.971	0.982
R^2 (log)	0.949	0.976	0.976
F^* (B_1, $B_2 \neq 0$)	—	475.81	468.55
F_c (B_1, $B_2 \neq 0$)	—	3.42	3.42
Stat. Hyp. Two (A)	—	Reject H_o	Reject H_o
F^* ($B_2 \neq 0$)	—	26.52	25.78
F_c ($B_2 \neq 0$)	—	4.28	4.28
Stat. Hyp. Two (B)	—	Reject H_o	Reject H_o
Residual Distn.	—	Acceptable	Acceptable
Criterion Test	—	Passed	Passed

Research Hypothesis Two Analysis Summary

For this research hypothesis the two statistical hypotheses and the criterion test were evaluated using fabrication labor hours and assembly labor hours, respectively, as the dependent variable. Both production rate variable proxies were again evaluated with each combination of data.

As was found for total labor hours under Research Hypothesis One, the full model showed overwhelming significance in Statistical Hypothesis Two (A) for all test situations. However, the production rate variable in Test Situation 5FM was not significant at the 0.05 level of significance under Statistical Hypothesis Two (B). In order to place this hypothesis test failure in better perspective the production rate variable in this test situation was significant at the 0.10 level of significance where F_c decreased to 2.94.

Although the production rate variable was not statistically significant at the prespecified 0.05 level for the one test situation, the sign of the B_2 coefficient was always negative. This implied that the inverse relationship between production rate variable and total labor hours variable held for the lower process levels of production also.

As to which production rate proxy gave the best results, the advantage of one over the other was again unclear. The full model with manufacturing rate did give better R^2 values in the first three situations for fabrication hours, but the full model with delivery rate excelled in the last two. For assembly hours the delivery rate gave higher R^2 values for every test situation, but the increase over R^2 values for the manufacturing rate was only about one percent in each situation. So, as in findings under Research Hypothesis One, neither proxy held a distinct advantage.

Finally, the criterion test was passed for all test situations with the exception of a mixed result in Test Situation 3AM. In this situation the R^2 (log) for the full model was higher than R^2 (log) for the reduced model, but the relationship was reversed for the R^2 (actual) statistics. In both instances, however, the difference in R^2 values was less than one percent which would seem insignificant. However, the F^* and F_c statistics under Statistical Hypothesis Two (B) indicated that the production rate variable's contribution to the explained variation (EV) was significant. Based on this additional information, the criterion test was deemed to have been passed.

RESEARCH HYPOTHESIS THREE ANALYSIS

Since a statistical hypothesis could not be developed to support testing this third research hypothesis, the following subjective criterion test was used. Specifically, the full model's predictive ability was accepted as good if the one year predictions did not deviate from observed values by more than five percent. The predictive ability of the model was tested against this criterion test for all test situations.

Since only historical data were available, predictions beyond the range of the data set obviously could not be evaluated. However, predictions into the future were simulated by regressing each model against the data set in each test situation with the last few cases omitted during regression. The regression coefficients obtained from these reduced data sets were then used to obtain predictions for the values in the omitted cases. Predictions by both the full and reduced models were thus obtained and the results were compared to the observed values in the omitted cases.

One complication arose in selecting the "target lot" for which predictions were to be made. For example, the multi-model combinations in the various lots presented

a dilemma in choosing a representative lot. Lot 40 was chosen on the basis that it contained a mixture of T-38/F-5 and special versions of the airframe (Ref. Table 5).

As in previous sections, the analysis is summarized in Table 17 and Appendix B. A brief description of table format and content is offered to assist interpretation.

Each table is divided into three horizontal sections. The center and bottom sections list information for the full model using the manufacturing rate and delivery rate, respectively. The top section lists information for the reduced model that corresponds to both full models.

The first column indicates the last case that was contained in the reduced data set for which regression coefficients were obtained. As a means of identifying trends in the predictive ability of the model as the predictive time span increased, the number of cases omitted was progressively increased from one to twelve. However, to reduce the volume of information in each table, data are recorded for every other data set rather than for all 12.

The asterisked number in this first column indicates the prediction time span that is closest to

one year. This time span was based on the date when the last airframe was accepted for the last lot (case), included in determining the regression coefficients, to the date of fabrication release of lot 40. This was deemed appropriate since all data, including these dates, were necessary inputs to the regression analysis. So, while on the average three or four lots were started each year, six cases were omitted in order to arrive at an approximate one year predictive time span for the situations tested.

The B_0, B_1, and B_2 columns in each table indicate the coefficients obtained from regressing the corresponding number of cases. The next column indicates the predicted labor hours variable value for lot 40. The final column indicates the percentage deviation of the predicted value from the observed value.

Predictive Ability Tests for All Test Situations

Predictive ability test results for Test Situations 1TM/1TD are summarized in Table 17. Results for all other test situations are recorded in Tables 24 through 38 in Appendix B. Discussion concerning all test situation results is contained in the summary of this section of the chapter.

Table 17

Predictive Ability - Test Situation 1TM/1TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
		Reduced Model - 1TM/1TD			
38	masked	masked	—	1.94	-6.7
36			—	1.83	-12.0
34*			—	1.77	-14.9
32			—	1.73	-16.8
30			—	1.67	-19.7
28			—	1.63	-21.6
		Full Model - 1TM			
Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	masked	2.16	3.8
36				2.19	5.3
34*				2.19	5.3
32				2.24	7.7
30				2.22	6.7
28				2.22	6.7
		Full Model - 1TD			
Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	masked	2.14	2.9
36				2.12	1.9
34*				2.06	-1.0
32				2.02	-2.9
30				2.01	-3.4
28				1.99	-4.3

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 40) for which the observed value is 2.08 hours per pound.

* - Indicates approximate one year time span.

Research Hypothesis Three Analysis Summary

Since the one year predictive time span results are of primary interest, they are summarized in Table 18 for the 15 test situations analyzed with each model. Specifically, the number of test situations in which the deviation in each models' prediction was less than five percent and ten percent are indicated. Although the criterion test specified an arbitrarily chosen five percent as the acceptable deviation limit, the information for ten percent is also provided to give a better perspective of overall performance.

As indicated in Table 18, the full model gave better predictions far more often than the reduced model. Further, the full model with the delivery rate variable performed slightly better than the full model with the manufacturing rate variable.

When predictive performance by labor hour category was examined, the findings were mixed. For instance, the five percent deviation limit for total labor hours was exceeded three times with the manufacturing rate model and only once with the delivery rate model. The findings were similar for assembly hours but the advantage switched to the manufacturing rate model when

Table 18

One Year Predictions Vs Criterion Test Deviation Limits

Items of Interest	Reduced Model		Full Model Manufacturing Rate		Full Model Delivery Rate	
Deviation Limit	5%	10%	5%	10%	5%	10%
Total Number of Test Situations Examined	15	15	15	15	15	15
Number of Test Situations Within Limit For:						
Total Labor Hours	0	0	2	4	4	5
Fabric. Labor Hours	2	2	3	3	2	4
Assem. Labor Hours	0	1	2	4	3	4
Total Number Within Limits	2	3	7	11	9	13

fabrication hours were examined. The question of which labor hour category yielded the best predictive performance remained debatable.

When other than the one year predictive time spans were examined, a very strong trend was detected. In most test situations the predictions tended to get worse as the predictive time span increased. Specifically, the predicted values became progressively smaller. This trend was particularly pronounced for the reduced model predictions, which implied that the slope of the curve for the reduced model became progressively more shallow as production output increased.

In contrast to the downward trend in the reduced model's predictions, half of the full model results revealed either no detectable trend or a slight upward trend. Further, since almost all reduced model predictions fell below the observed values, the full model also had the overall effect of raising the predicted value.

In general then, the use of the full model, rather than the reduced model, for making predictions revealed two distinct advantages: (1) the predictive ability was substantially improved in the vast majority

of situations tested, and (2) the predictions showed greater stability over a broader range of predictive time spans.

SUMMARY OF OVERALL ANALYSIS AND FINDINGS

This chapter discussed and presented the manipulation and combining of data, analyzed the ability of the production rate variable to explain additional variations in the three labor hours categories, and finally, compared the predictive abilities of the reduced and full models. The following discussion integrates the various isolated conclusions and findings discussed in each previous section of the chapter.

First, the collection of data had one weakness that undoubtedly affected the analysis and findings to some extent. This weakness was the inability to obtain exact acceptance dates for the first eight lots of T-38 airframes. Since these dates were estimated from delivery schedules, some error in the production rate variable calculations existed for these early lots. However, since actual dates from subsequent lots compared very favorably with delivery schedule dates, the error was probably not large.

Another problem encountered was the inability of the reduced and full models to accommodate the sudden large increase in labor hour requirements for F-5E production. Although the DCPR weight also increased with the F-5E airframe, the weight increase was not substantial enough to smooth the labor hours per pound of airframe variable. On the other hand, less drastic design changes between other airframe models were accommodated very well by the full and reduced models.

The findings for Research Hypotheses One and Two were consistent with what was anticipated. The full model for all labor hour categories was overwhelmingly significant, and R^2 (actual) values were higher with the full model than with the reduced model in 29 of the 30 situations tested. In the one remaining situation (3AM) the reduced model's R^2 value was less than one percent greater than that of the full model.

Also under the first two research hypotheses, the production rate variable was found to be significant in 29 of the 30 situations tested. The one situation (5FM) where the production rate variable was not found to be significant at the prespec:.ied 0.05 level of significance, was significant at the 0.10 level.

Another anticipated finding concerning the production rate variable was that the B_2 coefficient was negative in every situation. The implication of this finding was that as the production rate variable increased the labor hours per pound variable tended to decrease.

The findings under Research Hypothesis Three were more ambiguous due to the subjective method of evaluation. However, the predictive ability of the full model was definitely better than that of the reduced model in the majority of situations. When the one year predictive time spans were examined, the full model with delivery rate outperformed the reduced model in 13 of the 15 situations tested. The full model with manufacturing rate performed better than the reduced model in 14 of the 15 situations.

Another significant finding under Research Hypothesis Three was that the reduced model results indicated a progressive reduction in the learning curve slope as the productions output increased. This was evidenced by the negative growth trend in predictions with the reduced model as the predictive time span was increased within each situation. That the introduction of the production rate variable of the full model stabilized this trend in approximately half of the test situations and reduced

the trend's severity in the remaining situations was noteworthy.

Other findings related to predictive ability were observed. First, no clear advantage in performance was demonstrated by either production rate variable proxy. Second, no performance advantage was ascertained for any of the three labor hour categories. The results were not markedly better for either of the production rate proxies or within any of the three labor hour categories.

Chapter 5

SUMMARY AND CONCLUSIONS

One very important aspect of acquiring new aircraft weapon systems is the need to accurately estimate their production costs. If such costs could be accurately estimated, budgets could be more firmly set, cost tradeoff analysis between acquisition of different weapon systems could be more heavily relied upon, and the embarassment of extensive cost overruns could be averted. While the need for accurate estimates is readily evident, reliable estimating techniques are not easily derived.

Perhaps the first step in solving the problem is to examine individual cost components one at a time. One such component is the cost of direct labor required to manufacture each aircraft, and considerable research has been conducted concerning these labor requirements. One particular area of research has focused on the portion of aircraft labor requirements needed to fabricate and assemble the aircraft's airframe, including the installation, but not the manufacture, of avionics and other add-on equipment. This later research area defines the portion of the aircraft cost estimating problem that was examined in this study.

PREVIOUS ESTIMATING TECHNIQUES AND RESEARCH

A traditional approach to estimating direct labor requirements in airframe production has involved the use of the standard learning curve model. Specifically, variations in direct labor requirements were assumed to be driven only by the cumulative output of produced airframes. While this standard model has had widespread acceptance in the aircraft industry and in the DoD, the need for improving the model has also been widely accepted.

One area for possible improvement is to include the rate of production, in addition to the already proven cumulative output, as an explainer of labor hour requirement variations. While the standard model implicitly assumes that production rate will increase as output increases if the available labor time is held constant, it does not systematically consider the impact of explicit production rate changes that could be dictated by forces external to the learning process.

Considerable research effort has been expended in developing models that consider the effect of explicit production rate changes. However, based on available literature, the research efforts reported in Chapter 2 showed an evolution of new models that held promise for

continued development. In particular, Smith's model and research approach were deemed worthy of validation and replication.

His approach was to modify the standard learning curve model by including a production rate variable in multiplicative form. The resulting model in general form is $Y = B_0 X_1^{B_1} \cdot X_2^{B_2} \cdot 10^{\epsilon}$, where:

Y represents the unit average direct labor hours per DCPR pound of airframe,

X_1 represents the cumulative output as in the standard model,

X_2 represents the production rate,

ϵ represents the statistical error term, and

B_0, B_1, and B_2 are regression coefficients.

Using this modified model, he examined production data for the F-4, F-102, and KC-135.

RESEARCH OBJECTIVES AND METHODOLOGY

The primary objective of this research was to identify the impact of production rate changes on the T-38/F-5 program using Smith's model and research approach. A second objective of validating Smith's model and approach was also achieved.

In order to evaluate the T-38/F-5 production program with Smith's model, several combinations of data

were devised within the full set of data. Five basic combinations of airframe models were used to generate cumulative output and production rate variables. The first two combinations were essentially equivalent to the data combinations that Smith used in his research. Within each basic combination, the three labor hour categories (total, fabrication, and assembly) were examined using each production rate proxy (manufacturing and delivery). This provided a total of 30 data set test situations for which the three research hypotheses were evaluated.

The method of analysis called for regression of each data set in order to evaluate each statistical hypothesis devised in support of the research hypotheses. Specifically, Research Hypotheses One and Two required regression to obtain the R^2 values and F statistics needed to determine the overall significance of the production rate variable. The model's B_2 regression coefficient was used to determine whether the production rate variable was positively or negatively correlated with labor hour variations. Finally, the regression coefficients for portions of the data in each test situation were needed to permit predictive ability testing.

CONCLUSIONS

An overwhelming majority of the findings in this research directly support the conclusions drawn by Smith. In a few instances, however, his conclusions require modification before they can be supported. In this context, the following discussion interprets the findings of this research as they relate to Smith's conclusions.

Smith's First Conclusion

Smith's first conclusion that there is a negative correlation between production rate and direct labor requirements is directly supported by the findings. Specifically, the B_2 coefficients are negative in every situation tested. This negative correlation indicates that if production rate is increased, the required labor hours per pound of airframe will decrease. Therefore, the findings in this research support and further validate his conclusion.

Smith's Second Conclusion

Smith's second conclusion was that both production rate proxies were important explainers of labor hour variations, and that the full model with manufacturing rate gave higher R^2 results than the full model

with delivery rate. The first part of this conclusion is strongly supported by findings in this research. The production rate variable was found to be statistically significant for all labor hour categories and production rate proxy combinations under Test Situations 1 and 2. The R^2 values in these test situations for total and fabrication labor hour categories are higher for the manufacturing rate than for the delivery rate. However, under the assembly hours category, the delivery rate R^2 values are slightly higher. So, the second part of his conclusion is only supported for total and fabrication labor hours in these test situations.

In the remaining test situations (3, 4, and 5), for which Smith developed no equivalents, his second conclusion is also only partially supported. In these situations, where only certain airframe models were examined, the production rate variable was statistically significant in all but one situation (5FM) at the pre-specified 0.05 level of significance. This finding gives quite strong support to the first part of his second conclusion. However, in these situations the delivery rate gave higher R^2 values in nine out of ten situations, which does not support the second part of his conclusion. Still, based on all the findings for

all test situations, it can be concluded that both production rate proxies are significant explainers of labor hour variations for each airframe model as well as labor hour variations for all models combined.

Smith's Third Conclusion

Smith's third conclusion was that comparison of R^2 values for the full and reduced models indicated that the full model fit the data better than the reduced model. The results for all permutations of Test Situations 1 and 2 again directly support this conclusion. The R^2 values obtained for the full model with both production rate proxies were higher than those obtained with the reduced model.

In Test Situations 3, 4, and 5 the conclusion was also supported, but in one situation (3AM) the R^2 (actual) value was higher for the reduced model by less than one percent. However, even in these situations where only selected airframe models were examined, support for the conclusion is strong.

Smith's Fourth Conclusion

Smith's fourth conclusion was that the full model explained fabrication labor hour variations more fully than assembly labor hour variations. However,

based on a comparison of the R^2 values derived in this research, the opposite conclusion must be drawn. For Test Situations 1 and 2 the full model with manufacturing rate gave slightly higher R^2 values under the assembly category, and much higher R^2 values for assembly with the delivery rate proxy. Further, with the exception of situations 3FM and 3AM, a comparison of R^2 values in Test Situations 3, 4, and 5 shows that assembly labor hours are more fully explained.

The ramification of these findings is that assembly labor hour requirements may be more sensitive than fabrication labor hour requirements to production rate changes. However, in light of Smith's findings which led to the opposite conclusion, perhaps the only logical compromise is that while both fabrication and assembly labor hour requirements are sensitive to production rate, no firm conclusion can be drawn as to which is more sensitive.

Smith's Fifth Conclusion

Smith's fifth conclusion was that the production rate variable stabilized and improved the predictive ability of the full model. The predictive ability results of the full model, as measured by percentage

deviation from observed values, were not as consistently good as the results that Smith found in his research. However, the full model's predictions were substantially better and more stable over a broader predictive time span range than the predictions given by the reduced model. In particular, the one year predictions of the full model for Test Situations 1 and 2 deviated by approximately five percent or less in nine out of twelve instances. In situation 2TM the deviation was -10.5, in 1FM it was 10.6, and for 2FD it was -13.0 percent. To put these deviations in perspective, however, the reduced model deviations were -14.0 percent, -14.6 percent and -26.8 percent, respectively, for these same situations. In Test Situations 3, 4, and 5 only seven of the twenty predictions fell within the five percent deviation limit. Again, however, in 18 of these situations the full model predictions were as good as or better than those of the reduced model.

So, while the predictive ability of the full model was not good enough to pass the arbitrarily selected five percent deviation criterion in all cases, it was substantially better than the reduced model's ability in the vast majority of situations tested. Not only were the predictions better, they were more stable

over a wider predictive time span. These findings, then, are supportive of Smith's fifth conclusion.

Smith's Sixth Conclusion

Smith's sixth and final conclusion was that trying to formulate a generalized cost model using coefficients obtained from various production programs should not be attempted. Support for this conclusion was found within the predictive ability test situations with no need to compare T-38/F-5 results against Smith's F-4, F-102, and KC-135 results. For instance, the regression coefficients often changed substantially within a given test situation as successive cases were omitted from the regressed data. This finding strongly supports his conclusion that coefficients should not be averaged between or even within production programs. The model coefficients must be tailored through regression analysis of the most current data available for a given program.

CLOSING REMARKS AND RECOMMENDATIONS

The objectives of this research were successfully achieved. In particular, the impact of the production rate on direct labor requirements was analyzed in detail and found to be substantial. Secondly,

because of this first achievement, further support and validation of Smith's model and approach were shown.

By combining the results of this research with those of Smith's research, the applicability of his model and approach have been successfully demonstrated for three fighter aircraft of different size, weight, and performance capability. Additionally, Smith's limited success in applying the model to the KC-135 program implies an even broader range of applicability.

Not only do these four aircraft programs demonstrate applicability of Smith's model to different aircraft types, they also represent applicability to the production techniques and strategies of different manufacturers. This lends added support to the proposal that production rate effects are indeed an important consideration when estimating labor requirements.

Finally, it is recommended that Smith's model and approach be used to forecast direct labor requirements for future production of airframes in an active production program. The consistency of research results indicates the model's potential reliability and worth to estimators in such an application.

APPENDIX A

REGRESSION ANALYSIS INPUT DATA

Table 19

Regression Analysis Variables For Test Situation 1

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
1	1.39	0.104	1.935	masked	masked	masked
2	3.00	0.104	2.069			
3	6.00	0.233	1.319			
4	10.00	0.196	1.304			
5	14.50	0.205	1.667			
6	24.50	0.874	3.689			
7	40.00	1.157	7.742			
8	57.50	1.473	18.387			
9	85.00	2.400	14.400			
10	121.00	2.680	10.693			
11	157.00	2.621	9.391			
12	193.00	2.720	9.643			
13	229.00	2.422	10.000			
14	265.00	2.488	10.588			
15	304.50	1.669	2.945			
16	344.00	2.541	10.000			
17	383.50	2.003	4.607			
18	426.50	2.774	9.485			
19	476.00	2.897	6.486			
20	526.50	2.891	12.385			
21	587.00	4.740	13.571			
22	667.00	5.316	15.849			
23	755.00	5.644	16.829			
24	848.50	3.775	7.179			

Table 19 (Continued)

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
25	945.00	4.516	9.639	masked	masked	masked
26	1037.50	4.897	14.914			
27	1125.50	3.570	7.139			
28	1212.50	4.497	11.435			
29	1294.00	3.811	8.897			
30	1371.50	3.277	6.226			
31	1459.50	4.381	8.182			
32	1549.50	2.839	3.649			
33	1628.50	3.463	7.857			
34	1681.50	1.312	3.295			
35	1727.50	2.855	7.241			
36	1775.50	1.781	7.333			
37	1809.50	1.680	5.198			
38	1843.50	1.533	4.648			
39	1909.00	4.388	9.966			
40	1986.50	2.515	4.957			
41	2036.00	2.026	6.029			
43	2070.00	2.468	23.636			
44	2113.50	2.084	3.758			
45	2194.50	3.519	7.214			
46	2271.00	2.034	5.821			
47	2328.00	2.971	8.774			
48	2390.00	3.131	7.592			

Table 20

Regression Analysis Variables For Test Situation 2

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
1	1.39	0.104	1.935	masked	masked	masked
2	3.00	0.104	2.069			
3	6.00	0.233	1.319			
4	10.00	0.196	1.304			
5	14.50	0.205	1.667			
6	24.50	0.874	3.689			
7	40.00	1.157	7.742			
8	57.50	1.473	18.387			
9	85.00	2.400	14.400			
10	121.00	2.680	10.693			
11	157.00	2.621	9.391			
12	193.00	2.720	9.643			
13	229.00	2.422	10.000			
14	265.00	2.488	10.588			
15	304.50	1.669	2.945			
16	344.00	2.541	10.000			
17	383.50	2.003	4.607			
18	426.50	2.774	9.485			
19	476.00	2.897	6.486			
20	526.50	2.891	12.385			
21	587.00	4.740	13.571			
22	667.00	5.316	15.849			
23	755.00	5.644	16.829			
24	848.50	3.775	7.179			

Table 20 (Continued)

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
25	945.00	4.516	9.639	masked	masked	masked
26	1037.50	4.897	14.914			
27	1125.50	3.570	7.139			
28	1212.50	4.497	11.435			
29	1294.00	3.811	8.897			
30	1371.50	3.277	6.226			
31	1459.50	4.381	8.182			
32	1549.50	2.839	3.649			
33	1628.50	3.463	7.857			
34	1681.50	1.312	3.295			
35	1727.50	2.855	7.241			
36	1775.50	1.781	7.333			
37	1809.50	1.680	5.198			
39	1909.00	4.388	9.966			
40	1986.50	2.515	4.957			
41	2036.00	2.026	6.029			
43	2070.00	2.468	23.636			
44	2113.50	2.084	3.758			
45	2194.50	3.519	7.214			
46	2271.00	2.034	5.821			
47	2328.00	2.971	8.774			
48	2390.00	3.131	7.592			

Table 21

Regression Analysis Variables For Test Situation 3

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
1	1.39	0.104	1.935	masked	masked	masked
2	3.00	0.104	2.069			
3	6.00	0.233	1.319			
4	10.00	0.196	1.304			
5	14.50	0.205	1.667			
6	24.50	0.874	3.689			
7	40.00	1.157	7.742			
8	57.50	1.473	18.387			
9	85.00	2.400	14.400			
10	121.00	2.680	10.693			
11	157.00	2.621	9.391			
12	193.00	2.720	9.643			
13	229.00	2.422	10.000			
14	265.00	2.488	10.588			
15	301.00	2.379	9.076			
16	337.00	2.541	10.000			
17	373.00	2.293	10.093			
18	409.00	2.323	8.640			
19	445.00	2.494	9.643			
20	477.50	2.170	20.233			
21	515.50	3.169	10.682			
22	562.50	2.975	10.144			
23	609.00	2.936	9.583			
24	656.00	3.090	13.333			

Table 21 (Continued)

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
25	704.00	3.117	13.585	masked	masked	masked
26	760.00	3.602	10,971			
27	806.50	1.863	33,462			
28	846.50	2,698	6,861			
29	895.00	2,248	8,263			
31	935.50	1.944	7.192			
32	975.00	2.218	9.635			
33	1031.50	3.103	10.000			
35	1093.00	2.447	6.207			
37	1128.00	0.768	2.376			
39	1146.00	0.938	3.141			
40	1167.50	1.015	4,367			
41	1183.00	0.416	5,455			

Table 22

Regression Analysis Variables For Test Situation 4

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
15	3.16	0.294	1.135	masked	masked	masked
17	10.50	0.344	4.773			
18	17.50	0.441	2.121			
19	31.00	1.034	3.409			
20	49.00	1.028	11.707			
21	71.50	1.809	8.788			
22	104.50	2.347	6.981			
23	146.00	2.822	8.415			
24	192.50	1.858	3.801			
25	241.00	2.290	4.918			
26	277.50	1.516	10.952			
27	319.00	2.406	4.813			
28	366.00	2.166	9.533			
29	399.00	1.832	5.549			
30	453.50	3.277	6.226			
31	524.00	2.832	5.304			
32	574.50	1.369	1.667			
33	597.00	0.397	1.034			
34	615.50	1.312	1.942			
35	634.50	0.483	3.462			
36	655.50	1.781	7.333			
37	681.50	0.955	3.295			
38	707.50	1.533	4.648			
39	763.00	3.493	7.932			

Table 22 (Continued)

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
40	819.00	1.917	5.178	masked	masked	masked
41	853.00	1.640	4.880			
43	883.00	2.468	23.636			
44	926.50	2.084	3.758			
45	1007.50	3.519	7.214			
46	1084.00	2.034	5.821			
47	1141.00	2.971	8.774			
48	1203.00	3.131	7.592			

Table 23

Regression Analysis Variables For Test Situation 5

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
15	3.16	0.272	1.135	masked	masked	masked
17	10.50	0.326	4.773			
18	17.50	0.452	2.121			
19	31.00	1.034	3.409			
20	49.00	1.028	11.707			
21	71.50	1.809	8.788			
22	104.50	2.342	6.981			
23	140.50	2.323	11.053			
24	176.00	1.423	2.911			
25	213.50	2.276	7.134			
26	244.50	1.295	10.952			
27	278.00	1.765	3.529			
28	317.00	1.799	9.533			
29	344.50	1.425	6.923			
30	393.50	3.277	6.226			
31	447.50	1.655	6.940			
32	480.00	1.303	1.532			
33	501.00	0.360	1.034			
34	511.50	0.628	0.961			
35	522.50	0.483	3.462			
36	535.50	0.931	4.250			
37	553.50	0.912	3.295			
39	582.50	1.746	3.966			
40	606.00	0.451	1.224			

Table 23 (Continued)

Lot Number	Cumulative Production Plot Point	Lot Average Manufacturing Rate	Lot Delivery Rate	Fabrication Hours Per Pound	Assembly Hours Per Pound	Total Hours Per Pound
41	618.50	0.820	2.440	masked	masked	masked
43	628.00	0.190	3.000			
44	638.50	0.649	1.170			
45	668.50	1.396	2.929			
46	700.00	0.860	2.463			
47	742.00	2.971	8.774			
48	804.00	3.131	7.592			

APPENDIX B

PREDICTIVE ABILITY TEST RESULTS

Table 24

Predictive Ability - Test Situation 1TM/1TD

Reduced Model - 1TM/1TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	—	1.94	-6.7
36			—	1.83	-12.0
34*			—	1.77	-14.9
32			—	1.73	-16.8
30			—	1.67	-19.7
28			—	1.63	-21.6

Full Model - 1TM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	masked	2.16	3.8
36				2.19	5.3
34*				2.19	5.3
32				2.24	7.7
30				2.22	6.7
28				2.22	6.7

Full Model - 1TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	masked	2.14	2.9
36				2.12	1.9
34*				2.06	-1.0
32				2.02	-2.9
30				2.01	-3.4
28				1.99	-4.3

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 40) for which the observed value is 2.08 hours per pound.

* - Indicates approximate one year time span.

Table 25

Predictive Ability - Test Situation 1FM/1FD

Reduced Model - 1FM/1FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	—	1.11	-9.8
36			—	1.08	-12.2
34*			—	1.05	-14.6
32			—	1.01	-17.9
30			—	0.96	-22.0
28			—	0.93	-24.0

Full Model - 1FM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	masked	1.34	8.9
36				1.36	10.6
34*				1.36	10.6
32				1.39	13.0
30				1.36	10.6
28				1.30	5.7

Full Model - 1FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	masked	1.30	5.7
36				1.28	4.1
34*				1.24	0.8
32				1.20	-2.4
30				1.17	-4.9
28				1.11	-9.8

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 40) for which the observed value is 1.23 hours per pound.

* - Indicates approximate one year time span.

Table 26

Predictive Ability - Test Situation 1AM/1AD

Reduced Model - 1AM/1AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	--	0.75	-11.8
36			--	0.74	-12.9
34*			--	0.73	-14.1
32			--	0.72	-15.3
30			--	0.71	-16.5
28			--	0.71	-16.5

Full Model - 1AM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	masked	0.83	-2.4
36				0.83	-2.4
34*				0.83	-2.4
32				0.86	1.2
30				0.87	2.4
28				0.92	8.2

Full Model - 1AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
38	masked	masked	masked	0.83	-2.4
36				0.83	-2.4
34*				0.82	-3.5
32				0.82	-3.5
30				0.84	-1.2
28				0.87	2.4

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 40) for which the observed value is 0.85 hours per pound.

* - Indicates approximate one year time span.

Table 27

Predictive Ability - Test Situation 2TM/2TD

Reduced Model - 2TM/2TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
37	masked	masked	—	1.83	-8.5
35			—	1.77	-11.5
33*			—	1.72	-14.0
31			—	1.69	-15.5
29			—	1.63	-18.5
27			—	1.61	-19.5

Full Model - 2TM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
37	masked	masked	masked	2.16	8.0
35				2.16	8.0
33*				2.21	10.5
31				2.24	12.0
29				2.15	7.5
27				2.19	9.5

Full Model - 2TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
37	masked	masked	masked	2.10	5.0
35				2.05	2.5
33*				2.01	0.5
31				2.03	1.5
29				1.95	-2.5
27				1.95	-2.5

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 39) for which the observed value is 2.00 hours per pound.

* - Indicates approximate one year time span.

Table 28

Predictive Ability – Test Situation 2FM/2FD

Reduced Model – 2FM/2FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
37	masked	masked	—	1.09	-21.0
35			—	1.05	-23.9
33*			—	1.01	-26.8
31			—	0.98	-29.0
29			—	0.93	-32.6
27			—	0.90	-34.8

Full Model - 2FM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
37	masked	masked	masked	1.35	-2.2
35				1.35	-2.2
33*				1.39	0.7
31				1.38	0.0
29				1.29	-6.5
27				1.26	-8.7

Full Model - 2FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
37	masked	masked	masked	1.29	-6.5
35				1.25	-9.4
33*				1.20	-13.0
31				1.18	-14.5
29				1.11	-19.6
27				1.07	-22.5

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 39) for which the observed value is 1.38 hours per pound.

* - Indicates approximate one year time span.

Table 29

Predictive Ability - Test Situation 2AM/2AD

Reduced Model - 2AM/2AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
37	masked	masked	—	0.74	-7.5
35			—	0.72	-10.0
33*			—	0.71	-11.3
31			—	0.71	-11.3
29			—	0.70	-12.5
27			—	0.71	-11.3

Full Model - 2AM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
37	masked	masked	masked	0.81	1.3
35				0.81	1.3
33*				0.83	3.8
31				0.89	11.3
29				0.87	8.8
27				0.94	17.5

Full Model - 2AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
37	masked	masked	masked	0.81	1.3
35				0.80	0.0
33*				0.80	0.0
31				0.83	3.8
29				0.84	5.0
27				0.87	8.8

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 39) for which the observed value is 0.80 hours per pound.

* - Indicates approximate one year time span.

Table 30

Predictive Ability - Test Situation 3TM/3TD

Reduced Model - 3TM/3TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
34	masked	masked	—	1.67	-11.2
32			—	1.63	-13.3
30*			—	1.59	-15.4
28			—	1.56	-17.0
26			—	1.54	-18.1
24			—	1.54	-18.1

Full Model - 3TM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
34	masked	masked	masked	2.06	9.6
32				2.00	6.4
30*				1.94	3.2
28				1.88	0.0
26				1.86	-1.1
24				1.88	0.0

Full Model - 3TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
34	masked	masked	masked	1.91	1.6
32				1.82	-3.2
30*				1.76	-6.4
28				1.71	-9.0
26				1.74	-7.4
24				1.76	-6.4

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 36) for which the observed value is 1.88 hours per pound.

* - Indicates approximate one year time span.

Table 31

Predictive Ability - Test Situation 3FM/3FD

Reduced Model - 3FM/3FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
34	masked	masked	--	0.99	-13.2
32			--	0.96	-15.8
30*			--	0.93	-18.4
28			--	0.89	-21.9
26			--	0.87	-23.7
24			--	0.87	-23.7

Full Model - 3FM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
34	masked	masked	masked	1.36	19.3
32				1.34	17.5
30*				1.27	11.4
28				1.22	7.0
26				1.16	1.8
24				1.22	7.0

Full Model - 3FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
34	masked	masked	masked	1.17	2.6
32				1.11	-2.6
30*				1.05	-7.9
28				0.99	-13.2
26				1.01	-11.4
24				1.00	-12.3

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 36) for which the observed value is 1.14 hours per pound.

* - Indicates approximate one year time span.

Table 32

Predictive Ability - Test Situation 3AM/3AD

Reduced Model - 3AM/3AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
34	masked	masked	—	0.68	-8.1
32			—	0.67	-9.5
30*			—	0.67	-9.5
28			—	0.67	-9.5
26			—	0.68	-8.1
24			—	0.68	-8.1

Full Model - 3AM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
34	masked	masked	masked	0.74	0.0
32				0.70	-5.4
30*				0.69	-6.8
28				0.69	-6.8
26				0.73	-1.4
24				0.73	-1.4

Full Model - 3AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
34	masked	masked	masked	0.74	0.0
32				0.71	-4.1
30*				0.71	-4.1
28				0.72	-2.7
26				0.74	0.0
24				0.75	1.4

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 36) for which the observed value is 0.74 hours per pound.

* - Indicates approximate one year time span.

Table 33

Predictive Ability - Test Situation 4TM/4TD

Reduced Model - 4TM/4TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
23	masked	masked	—	2.08	-5.9
21			—	2.06	-6.8
19*			—	1.97	-10.9
17			—	1.88	-14.9
15			—	1.78	-19.5
13			—	1.71	-22.6

Full Model - 4TM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
23	masked	masked	masked	2.09	-5.4
21				2.07	-6.3
19*				2.03	-8.1
17				2.00	-9.5
15				1.90	-14.0
13				1.85	-16.3

Full Model - 4TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
23	masked	masked	masked	2.35	6.3
21				2.30	4.1
19*				2.23	0.9
17				2.19	-0.9
15				2.18	-1.4
13				2.10	-5.0

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 25) for which the observed value is 2.21 hours per pound.

* - Indicates approximate one year time span.

Table 34

Predictive Ability - Test Situation 4FM/4FD

Reduced Model - 4FM/4FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
23	masked	masked	—	1.35	5.5
21			—	1.33	3.9
19*			—	1.29	0.8
17			—	1.22	-4.7
15			—	1.17	-8.6
13			—	1.11	-13.3

Full Model - 4FM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
23	masked	masked	masked	1.35	5.5
21				1.34	4.7
19*				1.32	3.1
17				1.28	0.0
15				1.20	-6.3
13				1.14	-10.9

Full Model - 4FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
23	masked	masked	masked	1.34	4.7
21				1.32	3.1
19*				1.28	0.0
17				1.26	-1.6
15				1.22	-4.7
13				1.17	-8.6

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 25) for which the observed value is 1.28 hours per pound.

* - Indicates approximate one year time span.

Table 35

Predictive Ability - Test Situation 4AM/4AD

Reduced Model - 4AM/4AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
23	masked	masked	--	0.76	-17.4
21			--	0.75	-18.5
19*			--	0.73	-20.7
17			--	0.69	-25.0
15			--	0.66	-28.3
13			--	0.66	-28.3

Full Model - 4AM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
23	masked	masked	masked	0.77	-16.3
21				0.76	-17.4
19*				0.75	-18.5
17				0.74	-19.6
15				0.71	-22.8
13				0.72	-21.7

Full Model - 4AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
23	masked	masked	masked	0.75	-18.5
21				0.75	-18.5
19*				0.72	-21.7
17				0.72	-21.7
15				0.72	-21.7
13				0.73	-20.7

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 25) for which the observed value is 0.92 hours per pound.

* - Indicates approximate one year time span.

Table 36

Predictive Ability - Test Situation 5TM/5TD

Reduced Model - 5TM/5TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
22	masked	masked	--	2.11	-8.3
20			--	2.06	-10.4
18*			--	1.98	-13.9
16			--	1.89	-17.8
14			--	1.79	-22.2
12			--	1.75	-23.9

Full Model - 5TM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
22	masked	masked	masked	2.49	8.3
20				2.43	5.7
18*				2.40	4.3
16				2.27	-1.3
14				2.14	-7.0
12				2.14	-7.0

Full Model - 5TD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
22	masked	masked	masked	2.44	6.1
20				2.37	3.0
18*				2.34	1.7
16				2.36	2.6
14				2.17	-5.7
12				2.13	-7.4

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 24) for which the observed value is 2.30 hours per pound.

* - Indicates approximate one year time span.

Table 37

Predictive Ability - Test Situation 5FM/5FD

Reduced Model - 5FM/5FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
22	masked	masked	—	1.36	1.5
20			—	1.33	-0.7
18*			—	1.28	-4.5
16			—	1.22	-9.0
14			—	1.14	-14.9
12			—	1.10	-17.9

Full Model - 5FM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
22	masked	masked	masked	1.59	18.7
20				1.56	16.4
18*				1.51	12.7
16				1.40	4.5
14				1.29	-3.7
12				1.20	-10.4

Full Model - 5FD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
22	masked	masked	masked	1.55	15.7
20				1.51	12.7
18*				1.47	9.7
16				1.42	6.0
14				1.28	-4.5
12				1.24	-7.5

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 24) for which the observed value is 1.34 hours per pound.

* - Indicates approximate one year time span.

Table 38

Predictive Ability - Test Situation 5AM/5AD

Reduced Model - 5AM/5AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
22	masked	masked	—	0.78	-18.8
20			—	0.76	-20.8
18*			—	0.74	-22.9
16			—	0.78	-18.8
14			—	0.69	-28.1
12			—	0.70	-27.1

Full Model - 5AM

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
22	masked	masked	masked	0.89	-7.3
20				0.87	-9.4
18*				0.88	-8.3
16				0.83	-13.5
14				0.79	-17.7
12				0.89	-7.3

Full Model - 5AD

Cases	B_0	B_1	B_2	Forecast[a]	% Deviation
22	masked	masked	masked	0.88	-8.3
20				0.86	-10.4
18*				0.88	-8.3
16				0.88	-8.3
14				0.85	-11.5
12				0.87	-9.4

[a]Forecasts are made for the labor hours variable in Lot #40 (Case 24) for which the observed value is 0.96 hours per pound.

* - Indicates approximate one year time span.

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BIOGRAPHICAL SKETCHES

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Captain Duane E. Congleton graduated from Oregon State University, Corvallis, Oregon, in 1966 with a Bachelor of Science Degree in Civil Engineering. He received his commission from Officer Training School in September 1966. Since receiving his commission he has filled numerous crew and staff positions at squadron and wing level at several Minuteman Missile Bases. He was selected to attend the School of Systems and Logistics, starting in August 1976. Upon graduation he will be assigned to Warner Robins AFB, Georgia, as a Construction Manager under the Base Civil Engineer.

Major David W. Kinton graduated from Case Institute of Technology, Cleveland, Ohio, with a Bachelor of Science Degree in Engineering, in June 1965 and was commissioned through the Reserve Officer Training Corps. He entered active duty and pilot training in October 1965. Since completion of training he has flown KC-135 and EC-121R aircraft as both pilot and instructor pilot in both operational and combat crew training squadrons. Upon graduation from the School of Systems and Logistics he will be assigned to Brooks AFB, Texas, as Chief, Plans and Programs under the Base Civil Engineer.